Nanoscience and Nanotechnology: Opportunities and Challenges in California

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CCST is a nonprofit organization established in 1988 at the request of the California State Government and sponsored by the major post-secondary institutions of California, in conjunction with leading private-sector firms. CCST's mission is to improve science and technology policy and application in California by proposing programs, conducting analyses, and recommending policies and initiatives that will maintain California's technological leadership and a vigorous economy.

Acknowledgements

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PREFACE FROM CALIFORNIA COUNCIL ON SCIENCE AND TECHNOLOGY

The California Council on Science and Technology's charge is to assess California's long-term research needs, its ability to retain vital industries and scientific talent, its ability to transfer technology from university lab to industry, and S&T public policy issues. Nanotechnology poses unprecedented challenges in all these areas, and it is in the hope of laying the groundwork for producing a long-term, comprehensive nanotechnology strategy that CCST was asked to undertake this project.

The Joint Committee on Preparing California for the 21st Century has asked CCST to prepare this briefing as a part of its investigation into the social, legal, and ethical implications of emerging technology applications. This briefing provides an up-to-date perspective and analysis on numerous aspects of nanotechnology, including, among others, its economic impact; affected scientific disciplines; commercial best practices; workforce development issues and social and ethical issues. The briefing is not a comprehensive study, but rather a snapshot of where we are and where this technology is leading us. A state nanotechnology strategy, along with specific recommendations, is provided based on our current knowledge.

California is the nation's high tech leader, and most indices tell us it is the best suited to take the lead in nanotechnology. But there are serious issues to address if California is to stay ahead of the nanotechnology curve. We have all the right ingredients to make California the nanotechnology leader for the 21st century, and it is our hope that this briefing will help the state achieve this vision.

Many individuals have contributed to this briefing, which has been prepared under the direction of the CCST New Technology Committee, with Art Chester and Robert Spinrad presiding over the project, and with valuable assistance from Meyya Meyappan, senior scientist for nanotechnology at NASA Ames. Each has contributed substantially to the project and worked to maintain the inclusive perspective and cutting-edge focus of the briefing.

We would like to thank the Joint Committee on Preparing California for the 21st Century for requesting this briefing and providing a necessary and valuable focus on nanotechnology. We also extend our appreciation to the Semiconductor Industry Association (SIA) and the California Technology, Trade, and Commerce Agency for their generous support.

C. Judson King, Council Chair

Susan Hackwood, Executive Director

CALIFORNIA'S FUTURE IN NANOTECHNOLOGY
SENATOR JOHN VASCONCELLOS AND ASSEMBLYMEMBER SARAH REYES

21st Joint Committee on Preparing California for the 21st Century

December 12, 2003

Susan Hackwood
Executive Director
California Council on Science
and Technology
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Susan --

Thank you to the California Council on Science and Technology (CCST) for preparing a truly remarkable briefing on the emerging fields of Nanotechnology and Nanoscience in California. Once again, CCST has risen to the challenge and provided us with information that is *absolutely* crucial to the policymaking process. Your efforts are commendable.

As this briefing clearly demonstrates, the next wave of technological revolution is here. "Nano" is already part of sunscreen, clothing and tennis balls. When nanoscience and nanotechnology reach their full potential, key California industries will morph dramatically -- causing social, environmental and economic transformations of an utterly unforeseeable scope and scale. Whether these technological advances are good or bad for California depends in no small part on how smartly and creatively we manage them, and on the investments we make for our economic future.

Historically, California's many high-tech assets -- strong research centers, available venture capital, well-trained workforce, and our culture of innovation -- have contributed significantly to our leadership in the global economy. These same assets could serve us again. We have an opportunity to lead the field with nano, if this is the path we choose to take. However, the emergence of nano presents us with several strategic questions. How can we best gain the advantages of nano? How do we minimize any potentially harmful consequences? Will we grow and use this foundation well, or will we focus our attention elsewhere? The stakes are high. Our prosperity is on the line.

With this important briefing, the California Council on Science and Technology has given policymakers serious and thoughtful insight into the opportunities and challenges facing us now. We look forward to working together towards a healthy, prosperous and very small future.

Sincerely --

Sarah

JOHN VASCONCELLOS
Senate Co-Chair

SARAH REYES
Assembly Co-Chair

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SIA | SEMICONDUCTOR INDUSTRY ASSOCIATION

January 4, 2004

Dr. Susan Hackwood
Executive Director
California Council on Science and Technology
University of California
Riverside, CA 92521

Dear Dr. Hackwood,

The SIA applauds the California Council on Science and Technology for its efforts to insure that California can take advantage of the opportunities offered by nanotechnology.

Arguably, semiconductor manufacturing already utilizes nanotechnology since the circuits on each chip are only 90 nanometers in length and some layers are only a few atoms thick. However, since these circuits are just smaller versions of the circuits that were made several decades ago, often the term "nanotechnology" is reserved for the revolutionary breakthroughs that will result in completely new electronic devices. We are quickly reaching the physical limits of our current technologies, and depend on nanotechnology research to extend the limits of our current processes through the introduction of new materials, and to eventually replace our current processes with completely new device structures.

SIA actively supports nanotechnology research, including the Gigascale Silicon Research Center led by the University of California at Berkeley and The Functional Engineered Nano Architectonics (FENA) Focus Center led by the University of California at Los Angeles. Seven other California universities also participate in these programs. California is also the home of many of the leading semiconductor manufacturers who will turn these research results into semiconductors that are many times faster and denser than today, and of many of the leading computer and software companies that will turn these nanoscale devices into products that will benefit consumers around the world.

SIA looks forward to working with the Council to share the important conclusions of this report with California's Congressional delegation and state government officials and legislators.

Sincerely,

George Scalise
President
Semiconductor Industry Association

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EXECUTIVE SUMMARY

California's high-tech industries – microelectronics, materials manufacturing, energy, biotechnology, biomedicine, computers – are on the verge of a dramatic, structural revolution, one that will change everything from what products are produced to how they are manufactured. This new industrial revolution is being driven by nanotechnology, which is the ability to work with matter at the molecular level, atom by atom. This ability has already enabled the creation of materials and systems whose structures and components exhibit novel and often significantly improved physical, chemical, and biological properties. California has traditionally been the nation's high-tech leader, and is as well-positioned as any state to take advantage of the changes. However, while California leads in some aspects of nanotechnology today, this revolution is so new and completely different that the dominance of any one region is not assured.

What is clear is that nanotechnology is big business. A few nanotechnology-created materials have already entered the consumer market, and many more are in the pipeline holding significant promise. Economists predict a trillion dollar global multi-industry market for nanoproducts over the next ten years. The federal government is investing $847 million in the National Nanotechnology Initiative this year to support research and development. In addition, the Nanotechnology Research and Development Act of 2003 recently passed, which provides an additional $3.68 billion over three years for nanotechnology R&D under the auspices of the U.S. Department of Energy, the National Science Foundation, the National Aeronautics and Space Administration (NASA), the U.S. Department of Commerce, and the Environmental Protection Agency.[1] Moreover, it is estimated that over $1.2 billion of venture capital was invested in nanotechnology during 2003.

Other nations have recognized the economic potential of nanotechnology; today, over 50 countries are at an early stage in nanotechnology development. Japan and several European countries are investing significant resources in research and training. Japan's spending, in particular, has outpaced that of the National Nanotechnology Initiative for several years.

We have some knowledge on how to proceed when faced with new technologies possessing potentially significant impact. Many lessons learned from the microelectronics and biotechnology industries are applicable to nanotechnology, and a comparison with biotechnology, in particular, shows a similar rise in patenting and publication during the first decade of each science. As is typical for previous scientific breakthroughs, there is a concentration of knowledge in a few scientists and engineers who are pushing the frontiers of nanotechnology. Factors important to the success of previous high-tech industries are certain to play similar roles for nanotechnology, such as the support of top university researchers and their ability to play leading roles in the formation of new firms; technology transfer to existing firms; tax and regulatory climates which encourage entrepreneurship; and the presence of a skilled workforce. Taken as a whole, the scientific and patenting growth of nanotechnology is at least the same order of magnitude as biotechnology when it was at a similar stage of development.

However, there are a few things about nanotechnology that pose unique and unprecedented challenges to California and the nation as a whole. One is the sheer scope of nanotechnology. It actually represents a collective advance to the nanoscale in several disciplines; biology, chemistry, and physics are all benefiting from, and being transformed by, the ability to study and work with

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[1] National Nanotechnology Initiative http://www.ostp.gov/NSTC/html/iwgn/iwgn.fy01budsupp1/nni.pdf.

matter at the scale of the individual atom or molecule. Significant advances in microelectronics and materials are projected for the near future, while down the road the possibility of quantum computing, genetically specific drugs, and near-flawless materials constructed to a high degree of molecular accuracy defy our ability to accurately predict the full implications of nanotechnology. This very scope, combined with a lack of accurate information, has led to public concern and fear about implausible applications such as self-replicating nanobots, leading some to call for a moratorium on nanotechnology research, even though this would bring research to a halt in many areas of biology, chemistry, and physics. Consequently, keeping the public informed about nanotechnology is particularly important. In addition, some of California's existing industries will have to undergo radical transformations in order to survive such changes as a shift from silicon-based computer chips to carbon nanotube-based chips, which would require adopting completely different manufacturing processes. Intellectual property (IP) is also an issue, both because nanotechnology enters uncharted territory (can one patent an atom?) and because of the inefficiency in the transfer of IP between universities, state agencies, and industry. California's increasing and well-documented difficulty in educating a sufficiently skilled workforce to support its high-tech industries, including nanotechnology startups, is also an important issue to address.

Another significant challenge is that of the potential environmental and social impacts these products may have. Although commercial synthesis of nanomaterials has begun, there are few data on the impact large quantities of these materials will have on the environment or on human health. In order to proceed, risk-benefit analyses need to be built into the nanotechnology R&D process from the beginning, to effectively anticipate and deal with potential hazards or social issues as they arise, not after.

The following recommendations are drawn from the research in the first six chapters of this briefing, each of which analyzes a different aspect of nanotechnology and its implications for California. They provide a guideline for what needs to be done in order to ensure that California's technological, economic, and social leadership in nanotechnology can be maintained. A more detailed set of recommendations is presented in chapter 7.

California is the nation's high-tech leader and is home to several of the world's leading nanotechnology research institutions. But leadership does not come automatically, even to California: it must be planned for. If the state takes appropriate steps to leverage its existing advantages and to effectively cope with challenges that may arise, California should be able to maintain its leadership in nanotechnology in the decades to come. Now is the time to lay the foundation for this future.

California Congressional Delegation

I. **Bring federal money to California via the Boehlert-Honda Nanotechnology Act and the 21st Century Nanotechnology Research and Development Act.** This legislation authorizes $3.68 billion over the next four years for nanotechnology research and development programs at the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Commerce, NASA, and the Environmental Protection Agency. The California delegation should pay particular attention to the Government Industry Cosponsorship of University Research, the Molecular Foundry at Berkeley, and the NASA Ames nanotechnology program, all of which have important benefits to California.

S189, the 21st Century Nanotechnology Research and Development Act requires the creation of research centers, education and training initiatives, research into societal and ethical implications of nanotechnology, and efforts to transfer technology for commercial uses.

The delegation should also support NSF's planned investment for Nanoscale Science and Engineering for FY 2004-05.

California Legislature

I. **Create a Select Committee on New and Emerging Technologies in each house of the Legislature.** The Senate President pro Tempore and Speaker of the Assembly should create a Select Committee on New and Emerging Technologies in each house. Alternatively, the current Senate Subcommittee on New Technologies could expand its role to include nanotechnology.

II. **Create nanoethics centers.** Using existing resources, private donations and funding, and federal grants, request its chairs to introduce legislation in an appropriate committee to create one or more nanoethics centers in the state's higher education system for the assessment of nanotechnology's social and ethical implications.

III. **Examine public privacy of nanotechnology sensors and data**. Request the chair of the Senate Subcommittee on New Technologies to examine the impact of nanotechnology sensors and information processing on public privacy.

Governor's Office

The Governor should:

I. **Establish a Nanotechnology Research and Workforce Advisory Council.** The council should be staffed by the Governor's Office of Planning and Research and should include the Governor's Secretary of Education, representatives for UC, CSU, the state's private universities, CCST (as a member or technical advisor) and the California Community Colleges, the Secretary of Labor and Workforce Development Agency, the Secretary of Business, Transportation and Housing Agency, and business representatives such as Northern California Nanotechnology Initiative (NCnano), and others from nanotechnology clusters in the Los Angeles, San Diego, and San Francisco Bay Areas.

The Secretary of Education should:

II. **Create a K-12 Science and Engineering Initiative.** Immediately consider a range of K-12 initiatives that could improve the flow of students, particularly women and other underrepresented groups, into engineering and science careers. CCST and many other organizations have made a number of recommendations to improve science and engineering education and to link it to the community colleges and private institutions of higher learning that could guide this effort.

III. **Insure that nanotechnology is included in the state education science standards.**

The Governor's Office of Planning and Research should:

IV. **Identify outmoded tax incentives** whose value could be transferred to encourage nanotechnology development. Form a state-private industry partnership and to consult with the Commission on Tax Policy and the New Economy to identify existing tax incentives that could be terminated on a one-for-one basis and replaced dollar-for-dollar with new ones for nanotechnology.

College and University Systems

The University of California, California State University system and private universities should:

I. **Create a strategic higher education research and technician workforce training plan for California.** CCST should draw upon its members from all segments of California's higher education system to form a working group to create the strategy and to determine an appropriate means for implementing and tracking it.

II. **Develop a social science nanotechnology curriculum.** The higher education system needs to develop new social science electives as part of undergraduate and graduate curricula to train social scientists to identify and track the risks and benefits of nanotechnology as the technology emerges.

III. **Encourage and attract public and private financing**. Involved institutions should pursue funding as a consortium.

The California Community Colleges Chancellor's Office, and the Dean of the Economic and Workforce Development Program should:

IV. **Inventory Industry Driven Regional Collaborative (IDRC) projects**. The goal would be to look for those linking business to college based workforce training to determine which lessons learned might be applicable to industry driven nanotechnology workforce training.

V. **Establish a nanotechnology workforce training initiative**. A portion of existing IDRC resources could be redirected in the normal funding process to begin development of a nanotechnology workforce training curriculum in each of the three nanotechnology regions. Industry and other higher education systems with significant nanotechnology research, or that have developed a nanotechnology undergraduate curriculum, should be invited to participate.

California State Government Agencies and Departments

I. **Form the Joint Nanotechnology Human, Agricultural, and Environmental Assessment Committee.** The Department of Health Services, Cal/OSHA, California Environmental Protection Agency, Department of Food and Agriculture, and other appropriate agencies and departments should, at the direction of the Governor, form the Joint Nanotechnology Human, Agricultural, and Environmental Assessment Committee. The committee membership should be drawn from each participating agency and develop a working relationship with CCST to provide technical expertise on an as-needed basis with the state's private and public universities and law schools, commensurate with available funding. The Committee should prepare a yearly briefing for the Governor and the Legislature.

The Labor and Workforce Development Agency should:

II. **Direct the Economic Strategy Panel, with support from the Labor Market Information Division, to identify the components, workforce development and other needs of emerging regional California nanotechnology clusters.**

III. **Direct the Labor Market Information Division, Employment Development Department, to permanently assign an analyst to monitor the emergence of the**

nanotechnology industry and related components in the three nanotechnology regions (Los Angeles, San Diego, and San Francisco Bay Areas).

IV. **Continuously update the California Training and Education Providers database** to identify nanotechnology related jobs. Industries to be listed include those involved in: biotechnology, catalysts, chemicals, coatings, devices, electronics, energy, fabrication, instruments, magnetics, materials, metals, mining, nanotubes, optics, packaging, powders, software, spintronics, and textiles.

V. **Instruct the Workforce Investment Board to identify nanotechnology as an emerging manufacturing industry cluster** that should be followed and the necessary training infrastructure appropriate to its stage of development put into place.

VI. **Involve nanotechnology oriented businesses and universities** that are actively transferring nanotechnology to industry when developing workforce training initiatives.

VII. **Train One-Stop staff** to understand and respond to specialized needs of high technology, and nanotechnology using or based on manufacturers in their immediate area. This means training One-Stop staff in the Los Angeles, San Diego, and the San Francisco Bay Area to be responsive to nanotechnology company training needs.

VIII. **Involve university, workforce training, and business** in developing and modifying a workforce training strategy for the industry.

IX. **Instruct the Employment Training Panel to develop goals, objectives and strategies** to enable the panel to increase small nanotechnology businesses' access to the Employment Training Panel program and services.

The Business, Transportation and Housing Agency should:

X. **Form Nanotechnology Regional Interagency Working Groups**. Work with the Regional Technology Collaborative in Los Angeles, and similar regional economic development groups including CalEd in San Diego, and San Francisco to form Nanotechnology Regional Interagency Working Groups.

CHAPTER 1: NANOTECHNOLOGY – WHY IS THIS A SPECIAL LENGTH SCALE?

Sandip Niyogi
Robert C. Haddon
University of California, Riverside

Key Points in this Chapter:

In the next 5 to 10 years...

Current manufacturing methods will reach their limits

- Conventional integrated circuits will decrease in feature size, nearing the point where silicon circuits become unreliable
- Nanomaterials based devices will become widely available

In the next 10 to 20 years...

A nanotechnology electronics revolution will take root

- Non-silicon computing devices with seamless integrated circuits 1 nanometer in diameter will require new manufacturing plants and processes
- Nanomedical devices implanted in humans will enable significant advances in disease prevention, diagnosis and control

1.1 Introduction

The word nanotechnology comes from the term nanometer, which is just a scale of measurement. Why should a length scale elicit such excitement? First we will attempt to give an indication of how big (or perhaps how small) a nanometer really is and then we will discuss why this length scale is important and why the potential of its mastery has caught the attention of the populace on a scale not seen since the birth of the space age.

A meter is about a yard, and there are 1,000,000,000 nanometers in a meter. If people were the size of nanometers, all of the people who ever lived on the planet could line up within a parking space. So what is a nanometer? It is about the size of a medium-sized molecule, say a molecule containing 60 carbon atoms.

> If people were the size of nanometers, all of the people who ever lived on the planet could line up within a parking space.

Well if small is good why not go smaller? Why not go to picotechnology? In this case we would divide a meter into 1,000,000,000,000 pieces of equal length (picometers). But this presents a problem – of what will those pieces consist? In nanotechnology we are down to atoms or small groups of atoms (molecules) as the building block, and molecules and atoms are everywhere on the planet – the rivers and oceans mainly consist of one small molecule: H_2O (water). But if we wish to cross into picotechnology we must find our fundamental unit, our building block for this technology. It cannot be atoms or molecules – they are hundreds of picometers in diameters. Using atoms or molecules on this length scale would be like trying to repair a watch with a jack-hammer.

In fact to get to the picometer scale it is necessary to split the atom – to generate subatomic particles such as protons, neutrons and electrons. However, the energy scale for the existence of such free particles is not appropriate for the surface of the planet because it takes a great deal of energy to split the atom. So there is not likely to be a picotechnology on the planet for some time. It is in this sense that nanotechnology represents a limit, a final frontier in the relentless drive for miniaturization for which the semiconductor industry is so well known.[1] But the semiconductor industry is just the most visible manifestation of the importance of miniaturization, because as we show in this chapter, virtually all of the physical, biological and engineering sciences are vitally concerned with this subject, although up to now, man made architectures could not begin to deal with the nanometer length scale.

The semiconductor industry is an attractive lens through which to view the ascendancy of nanotechnology because Moore's law is well known and because the semiconductor companies did not set out to become involved with nanotechnology. Their success is now forcing the industry to take notice of the subject. The semiconductor industry would have started to bump up against some of the more important issues in nanotechnology even if no one had thought to coin the term. It was not so long ago that the central processing unit in a computer which is responsible for processing information, required individual components that were 1,000s of nanometers in size – well beyond the realm of nanotechnology. Now, however the semiconductor industry routinely manufactures specific components on the size scale of a few hundred nanometers.[2] Figure 1.1 is

What are nanoscience and nanotechnology?

- The words nanoscience and nanotechnology both stem from the term nanometer, which is just a scale of measurement. A meter is about a yard, and there are one billion nanometers in a meter. This is the smallest scale at which we can meaningfully study and manipulate matter as we understand it.
- At the nanometer length scale, the laws of physics operate somewhat differently; the classical mechanics that we encounter in everyday life give way to quantum mechanics. At the nanoscale, for example, a tabletop is not smooth, but instead composed of discrete atoms and molecules.
- Nanoscience is a broad term used for the study of materials and/or processes at the nanoscale in a variety of disciplines. Biology, chemistry, and physics have all independently converged into nanoscientific research areas, ranging from everything to understanding intracellular processes to chemical interactions to quantum mechanics.
- Nanotechnology is the technological realization of quantum mechanics – the manipulation of materials and processes at the nanoscale level. This includes the design and manufacture of ever-smaller computer chips, custom-designed drugs, and materials with vastly increased strength due solely to the arrangement of their molecules (such as carbon nanotubules).
- Defining the scope of the subject is difficult. Ultimately the subjects of nanoscience and nanotechnology may disappear as separate disciplines, because they describe a mode of research and application rather than a unique field of study.

[1] International Technology Roadmap for Semiconductors (ITRS). 2002 Edition, Semiconductor Industry Association: http://public.itrs.net/.

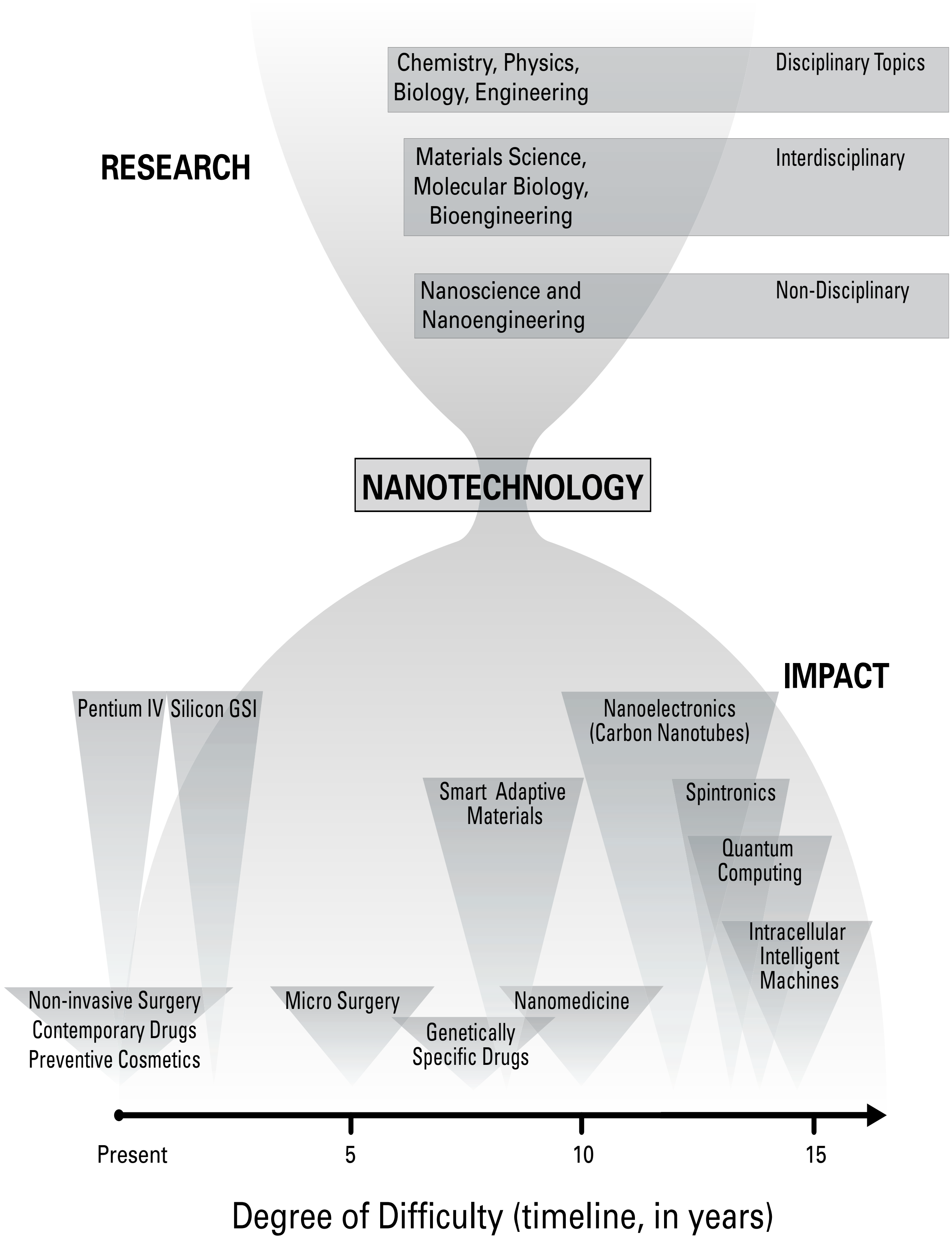

Figure 1.1: Author's Estimation of Nanotechnology Research and Potential Impact, with Projected Timeline to Significant Developments
Source: Robert Haddon, UCR

the authors' estimation of the overall outline of the evolution and scope of disciplines and high-tech innovations affected or potentially affected by nanotechnology.

Although the semiconductor industry provides a very nice illustration of the progression of an industry toward nanotechnology, there is an even better example of the power of this technology that has been around since the beginning of time.[3] Biology seems to have incorporated nanotechnology from the very beginning. Even the most basic life forms use very small-scale structures to accomplish impressive feats. Our familiarity with life forms has removed our ability to marvel at the miracles accomplished in biology, but in fact much of the power of biology arises out of structures and devices that operate at the nanometer length scale. One of the most impressive feats in biology is the transmission of information between generations, so that each new generation does not have to re-develop the blueprint for the species. Much of this information is contained in a biopolymer known as DNA that has a diameter of a couple of nanometers.[4,5] Figure 1.2 compares biological nanoscale phenomena with current nanotechnology.

So nanotechnology is both old and new, top down and bottom up – but mostly it is about size. Now we should ask about our ability to shrink things. Can we really shrink people so that the whole human race can line up in a parking space? Clearly the answer is no – we do not have access to objects small enough to construct nanometer-sized people. But what happens as we try to work with smaller objects – objects that consist of smaller numbers of our atomic and molecular building blocks? In short, is small just small or is it small and different. We shall draw some distinctions at this point, because nanotechnology forces us to come to grips with the graininess of matter. At the nanometer length scale a tabletop is not smooth – there are discrete atoms and molecules and to some extent they have their own individuality and lack of individuality. In other words we are entering the realm of quantum mechanics and it is different from the classical mechanics that we encounter in everyday life. Quantum mechanics takes over when matter becomes grainy; that is, where the size scale has shrunk to the point that matter no longer appears as a continuum. However the graininess is not restricted to matter, but also extends to energy and light and other properties.

But let us enter this nanoworld by degrees and consider some of the consequences of losing classical mechanics and the smooth world that is so familiar. Perhaps the first thing to be lost is sight – the ability to magnify objects and to observe them with an optical microscope. This is because the graininess or quantum nature of light starts to emerge on the nanometer length scale.

We are all familiar with the colors of the rainbow – these colors are due to variations in the wave length of the light; that is, the distance from crest to crest of the (electromagnetic) light waves. The wavelengths of light that can be seen by the human eye extend from 380 nanometers (violet) to 780 nanometers (red) with the other colors occurring at wave lengths in between these extremes. These wave lengths are important for more than the colors that they produce in the human eye – they also determine the resolving power of the light wave. It is perhaps not surprising that a

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2 Henton, Doug, et al., Preparing for the Next Silicon Valley. Opportunities and Choices. June 2002, Joint Venture: http://www.jointventure.org/.

3 Haddon, R. C. and A. A. Lamola, The Molecular Electronic Device and the Biochip Computer: Present Status. Proc. Natl. Acad. Sci., USA, 1985. 82: p. 1874-1878.

4 DOE, U.S., Complex Systems, C.V. Shank, Editor. 1999: http://www.science.doe.gov/bes/NNI.htm/.

5 BES, DOE, Nanoscale Science, Engineering and Technology in DOE's Office of Basic Energy Sciences. Research directions and nanoscale science research centers. 2003: http://www.science.doe.gov/bes/NNI.htm. p. 20.

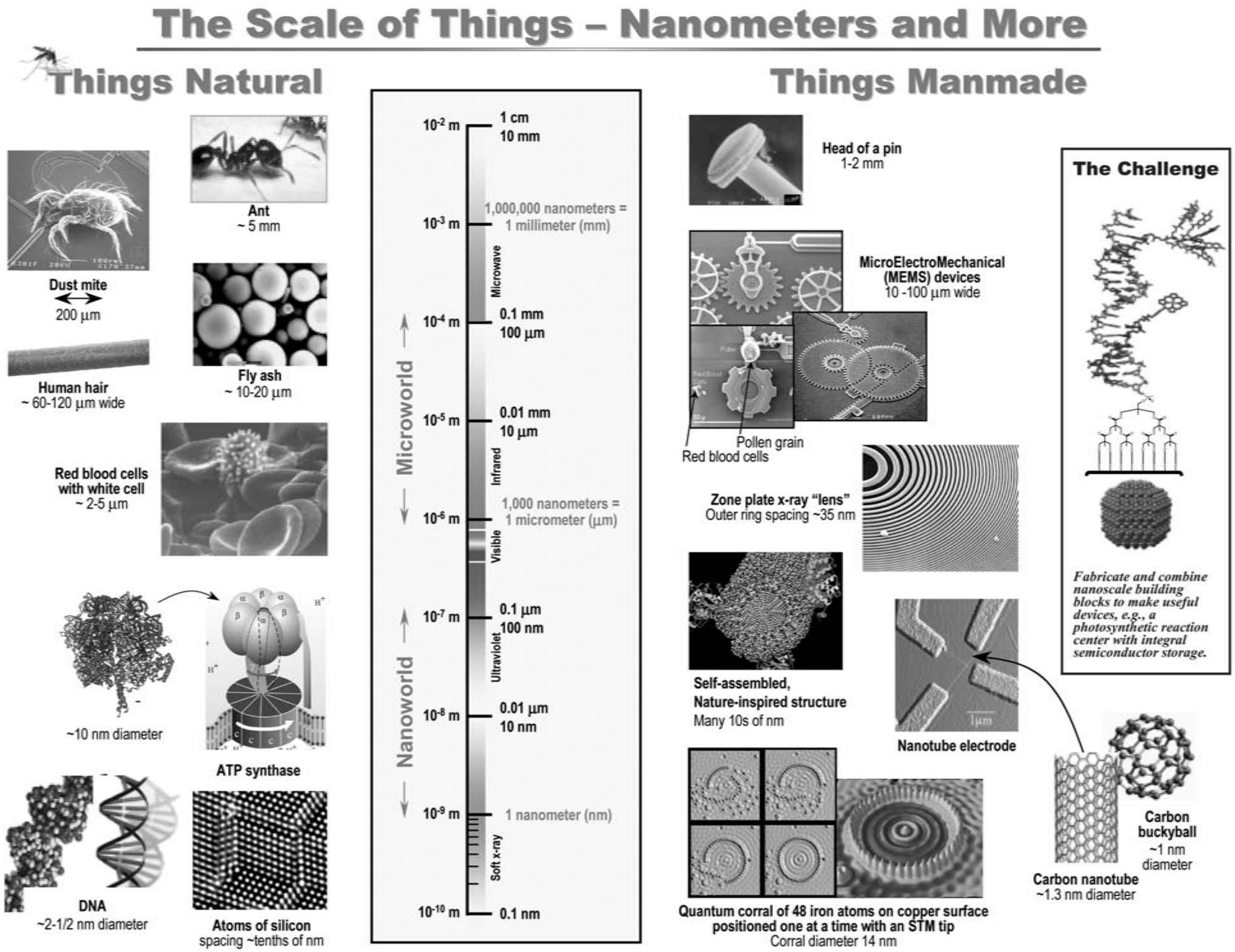

Figure 1.2: The Scale of Things
Source: Office of Basic Energy Sciences, Office of Science, U.S. DOE, version 10-07-03, pmd

ray of light can only resolve objects that are larger than its wave length. Consequently, objects smaller than about 400 nanometers will always be invisible to the human eye, irrespective of the degree of optical magnification. Thus the nanoworld is dark and unfamiliar to humanity, and will never be seen directly. Nevertheless, it can be imaged by using beams that are of much shorter wavelength than everyday light. Most commonly beams of electrons are used to provide electron micrographs. Beams of electrons? Every student of physics and chemistry knows that an electron is a particle – and a wave! In the nanoworld, determinism is one of the first casualties. We have literally entered the world of Rod Serling – The Twilight Zone.

In its most arcane form, nanotechnology is the technological realization of the subject discovered in the early 1900s – quantum mechanics. Quantum mechanics overthrew many of the dogmas that had been taken as gospel for so long. Once quantum mechanics had been accepted, everything that had gone before was relegated to "classical mechanics." Classical mechanics is entirely adequate for almost everything that occurs in everyday life, or rather on the scale of sizes and energies that are compatible with life – including for example, the motion of a car and most, if not all of biology. This point should make it clear that nanotechnology is not just about quantum mechanics and what we shall refer to as quantum nanotechnology. The simple reduction in size to the point that we are dealing with atoms and molecules – where properties scale with size – is extremely important in its own right. The quantum aspects, however, must be discussed separately because there is simply no parallel for these effects in the macroworld that we inhabit on a day-to-day basis.

How will nanotechnology be applied in major manufacturing sectors?

- By 2007, nanotechnology is predicted to exert a substantial impact on industries including healthcare products, chemicals, computers, and the telecom industry. In addition to the new products reaching the consumer market, ranging from lighter and stronger plastics used in cars to carbon nanotubule reinforcements in tennis rackets, there will be changes in how these products are made, as well as how non-nanoscale products are made.
- The most significant changes which are likely to affect California's industries in the near future are applications in the semiconductor industry. There is currently much discussion about the point where computer chips can no longer be scaled to smaller dimensions, a point that is now in sight. By 2010, projections suggest that chips will achieve a scale where silicon circuits no longer function well, and new materials will need to be used. The challenges inherent in switching to new materials will require the semiconductor industry to make substantial changes in their manufacturing process.
- It is difficult to assess the full extent to which manufacturing will be affected. The development of stronger materials with greater precision could have tremendous ramifications. Materials made with every atom exactly where it should be, perfect and free of defects, could be up to 1,000 times stronger than materials fabricated with current technology.
- Essentially, any industry depending on a high degree of precision and control in its manufacturing process could potentially be affected by nanotechnological materials and processes, regardless of whether or not the final product is a nanotechnology product.

1.2 Classical Nanotechnology

So we begin with a discussion of nanotechnologies where matter and energy can be reduced in size without the obvious intrusion of quantum phenomena, although it should probably be noted that at this size scale quantum mechanics is always operative; nevertheless, there are many situations which can be usefully discussed from the classical standpoint. Before taking up these subjects, a little more should be said about this division between classical and quantum nanotechnology just so the reader can appreciate what a fine line must be walked in achieving this somewhat arbitrary division. Let us return to water. It is comprised of molecules of H_2O, a simple molecule consisting of just three atoms. Describing the electronic structure of a water molecule – that is, the motion of the electrons in H_2O which hold the hydrogen and oxygen atoms together – requires the application of quantum mechanics. But chemists have learned how to approximate the forces that hold the atoms together by classical mechanics simply because there are imprecise analogs for these forces outside of quantum mechanics. Furthermore, there are also techniques to approximate the interaction between water molecules, and so approximate the liquid state by classical mechanics. In general, if there are classical analogs for a nanotechnology we will classify it as classical nanotechnology.

Thus to some extent our classification is observer dependent – if it can be understood by the observer within the normal sphere of experience it is classical nanotechnology, the rest falls into the province of quantum nanotechnology.

This makes classical nanotechnology seem rather ordinary, but we only have to look to biology to recognize the importance of classical nanotechnology. As yet, there is no evidence that quantum phenomena play a role in any aspect of biology.

In order for quantum effects to be ascendant there is usually some sort of extended state involved – that is, a state that involves many different atoms (or molecules), in a nonadditive manner. Typically this state will involve the motion of electrons or energy. As far as we know in most cases, the movement of charge in biology is accomplished by the motion of charged atoms – the ions. The motion of ions is responsible for most of the signaling and processing of information in biology, and the ions are too massive for quantum effects to be important. The retina is sensitive to light, but this energy is rapidly converted to chemical and mechanical energy. Likewise, the photosynthetic center uses light to generate electrons and their counterparts, but these are rapidly converted to chemical energy. Thus for the most part, the states that are involved in biology seem to be quite classical in nature.

Nevertheless, biology routinely achieves spectacular results by operating at the nanoscale. It is hard to comprehend the power of biology because life is so prolific and so much a part of our everyday life that we take it for granted.[6]

The cell is the basic unit of life forms, and the space the cell occupies is defined by an outer membrane. In man, it has a size of about 10,000 nanometers and the human body contains about 100,000,000,000 cells. Thus, it is immediately clear that biology works with small objects. However, each cell contains many compartments that allow diverse functions; one of those compartments, the nucleus, contains two meters of the DNA linear chain molecule. Thus, each cell contains the entire human genome – all of the information necessary to build a human being. How is this possible in such a tiny space? The answer is nanotechnology. Biology has developed a

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[6] May, Mike, Nanotechnology: Thinking Small, in Environmental Health Perspectives, NIEHS. 1999: http://ehpnet1.niehs.nih.gov/docs/1999/107-9/niehsnews.html.

way to encode information in a molecule (DNA) that is two meters long, but only two nanometers in diameter. The information exists in the DNA molecule as discrete and identifiable molecules that the machinery of the cell is able to decode and use as an instruction set for the actions that must be undertaken within the cell.

But the nucleus is just one of the many sub-cellular structures which are known as organelles. Within these organelles that are contained within cellular membranes, there is a high degree of order that allow the individual organelles to perform specific function(s). These organelles are involved in complex biochemical pathways involving the synthesis, sequestering or digestion of particular chemical species. Communication within the cell is regulated by the intracellular membranes that only allow the passage of certain chemicals, and the same applies to communication between the cells. Nevertheless, within the cell the transport of cellular components can be accomplished by molecular motors of dimension about ten nanometers that move on tracks that can be readily assembled to accomplish the needs of the cell.

However, these mechanical and chemical complexities do not hint at the sentience of life. Somehow this arises from the totality of these nanostructures – the unexpected capacity of information to be passed down from generation to generation by DNA, or the ability of a child to learn, utilizing neural signaling to process information to a very high degree in a manner which is still completely unexplained. Although the signaling pathways in the brain are some 100 nanometers in diameter, it is quite clear that if we are to understand and interrogate this complex structure, nanoprobes will be necessary.

So far we have chosen to exemplify classical nanotechnology by focusing on biology, but it is straightforward to imagine the power that this technology will have in manufactured items – simply consider what might happen if we could fabricate structures, objects and devices with the fidelity and precision that occurs routinely in biology. Materials made with every atom exactly where it should be, to be perfect and free of defects, would be 1,000 times stronger than materials fabricated with conventional technology.

> QUANTUM NANOTECHNOLOGY OFFERS THE POTENTIAL FOR EXCITING ADVANCES, BUT MAY ALSO POSE SIGNIFICANT CHALLENGES TO SOME INDUSTRIES.

1.3 Quantum Nanotechnology

Where will we first encounter quantum nanotechnology? Quantum mechanics has been a part of the sciences for almost a century, but it has not had a great deal of impact in engineering, manufacturing and business. Before proceeding, however, it is important to put this latter statement in context and to try and define the subject of nanotechnology a little more finely. As stated previously, the rivers and oceans are comprised of molecules of water (H_2O), and these molecules are only about a third of a nanometer in size. Does this mean that yachting and swimming require skill in nanotechnology? No, because nanotechnology implies some ability to control and direct processes on the nanoscale so that nano-objects are manipulated on an individual basis.

The realization of quantum nanotechnology offers the potential for exciting advances, but may also pose significant challenges to some industries. The occurrence of quantum phenomena will be – at least in some ways – unwelcome in the semiconductor industry. Again, the description of such effects is complicated because the industry is primarily dependent on the motion of charge carriers (electrons), which are inherently quantum mechanical entities. However, problems start to emerge when the silicon structures in which the electrons operate are reduced in size to the nanoscale. In this situation, unwelcome effects start to occur, mainly because the silicon starts to become grainy rather than continuous. In order for silicon to function as a semiconductor the states within which the electrons reside, depend on the presence of a large number of silicon atoms for their transport properties. When the device structures become nanosized and are composed of just a few atoms in a particular dimension, the current carrying states become quantized rather than continuous and do not allow the facile passage of current. Furthermore, at these small size scales the integrity of the devices is lost and cross-talk between structures that are supposed to be independent will start to degrade the integrity of the information.[7]

There is currently much discussion about the point where the current devices can no longer be scaled to smaller dimensions. The current Intel Pentium central processor contains over 55 million transistors with a minimum feature size of 130 nanometers. Current projections suggest that it will be possible to scale the conventional architecture so that the gate lengths in the transistors are reduced to 50 nanometers by 2010. Individual devices with even smaller dimensions have been constructed and tested but it remains to be seen whether they can be manufactured into reliable electronic components.

While conventional architectures may run into difficulties as a result of the intrusion of quantum effects, there is increasing interest in replacing silicon with other materials and structures that are tailored to exploit quantum nanotechnologies. We shall mention just one such material, because it seems uniquely structured for the nanoscale. The carbon nanotube may be thought of as a piece of graphite rolled up into a cylinder with a diameter of about one nanometer. Graphite is composed of sheets of carbon atoms arranged in the form of six-membered rings with a carbon atom at each vertex of the network so that the whole structure resembles chicken wire. Surprisingly, the resultant linear nanotube may be a metal or a semiconductor, depending on the exact details of the topology. Thus, it is possible for the carbon nanotube to supply the basic building blocks for an integrated circuit, as the metallic nanotubes can act as wires and the semiconducting nanotubes

What is needed to support nanotechnological manufacturing?

- Nanotechnologies are based on physical science; highly specialized equipment is necessary to do research and development. Many nano companies use or plan to use semiconductor like manufacturing facilities, which involve special "clean rooms," super clean water, and reliable backup power systems. Commercial disposal systems may be required in many cases as well.
- Setting up for nanotechnology R&D is expensive. An atomic force microscope, for example – a common piece of nanotech equipment – costs on the order of $100,000 for the least expensive model.
- Because nanotech companies are typically on the cutting edge of technology, there is not an existing well-developed infrastructure to build upon. Things that other companies can take for granted such as a technically trained workforce, manufacturing equipment, and design software are all minimal or nonexistent for nanotechnologies.

[7] Nanoscience and Nanotechnology: Shaping Biomedical Research, in BECON Nanoscience and Nanotechnology Symposium Report. June 2000, National Institutes of Health: http://grants.nih.gov/grants/becon/becon_symposia.htm.

could be fabricated into transistors. It is natural to ask why the nanotubes are not subject to the problems associated with quantum phenomena that were discussed above, and which were suggested to preclude the use of silicon on this size scale. In fact, the carbon nanotube profits from the intrusion of quantum phenomena. The carbon nanotube can be formed into a cylinder one atom thick to give a wire that is perfect – without defects. Furthermore, the states in the carbon nanotube are quantized in a particular manner so that the current carrying electrons do not undergo scattering. This allows the nanotube to pass current without resistance along its length and with very high current densities. Thus, if the carbon nanotubes could be organized into a seamless integrated circuit, there could be a new generation of computer components comprised of nanoelectronic devices.[8]

In the foregoing discussion, we suggested that the carbon nanotube might be used to replace the conventional materials used in silicon integrated circuits, to fabricate an even smaller generation of nanoelectronic devices that mimic the conventional semiconductor architecture. However, much more radical modifications to current computers are currently under consideration. For example, it is the charge on the electron that is used in the conventional semiconductors that comprise the central processing units and dynamic random access memories in computers today. For the nonvolatile memory, magnetic disk drives are used and these employ the spin of the electron to store large amounts of information and particularly to preserve the information when the computer is shut down. There is now the prospect of developing devices that simultaneously use both the spin and charge of the electron to vastly increase the capability of information processing, in what are called spintronic devices.[9]

What do we know about occupational and environmental risks?

- The impact of nanotechnology on the environment and on the dangers to human health is the most important one that needs to be studied. The commercial synthesis of functional materials with nanometer dimensions has begun, and few data exist on the impact these new materials will have on the environment in large quantities.
- In general, nanotechnology is likely to produce a wide range of materials of vastly different structures and natures, and there are currently limited data on potentially damaging effects. Preliminary data are available from a few studies, which suggest that some nanomaterials can cause inflammation of lung tissue and formation of microscopic lesions in rats. However, it is unclear whether these particulates pose actual risks when inhaled. It is not known whether or to what degree different nanometer scale materials may be able to enter the body through skin exposure.
- The Toxic Substances Control Act and the Food, Drug, and Cosmetic Act already require government review and certification of new chemicals before they can be produced and sold. These acts may need to be modified to account for toxicity resulting from size, but they do provide a framework for nanotech testing and approval.
- Because the potentially far-reaching consequences of nanotechnology are so diverse, it is essential to continually identify, assess, and respond to new environmental issues as they arise out of emerging scientific and technical research. However, it is important to recognize that many of the new nanotechnologies will not have direct environmental impacts.

[8] IBM's Research in Nanotechnology: http://www.research.ibm.com/pics/nanotech/.

[9] Wolf, S., Spin Transport Electronics (Spintronics), DARPA-DSO: http://www.darpa.mil/dso/thrust/matdev/spintron.htm.

Beyond this research direction, is the possibility of using quantum states to process and store information. At least in the conventional computer architecture, the manner in which information is processed and stored is entirely mechanical and the operation of these machines may be completely described by classical physics, although the components may function at a very small length scale. Thus, the information is encoded in binary format as in an on-off switch, and hence, it is always represented as a 0 or a 1 – a bit of information. It is possible that computers could be built to take advantage of quantum phenomena that have no analogue in the classical world with which we are familiar. This could be implemented if a way could be found to represent information by quantum states. Classical bits can be 0 or 1, but quantum bits (qubits), can be a linear superposition of these two classical states. This gives rise to many more states of the system, and thus in principle the ability to represent much more information without increasing the number of components – providing that it is possible to devise a way for the states of the system to interact quantum mechanically.[10]

What is the federal government doing in nanotechnology?

- The president's 2004 budget for the National Nanotechnology Initiative (NNI) increased funding from $774 million in 2003 to $847 million in 2004 – a 9.5% increase. In addition, the Nanotechnology Research and Development Act, signed in December 2003, allocates $3.68 billion over the next four years for nanotechnology research and development programs at the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Commerce, the National Aeronautics and Space Administration (NASA), and the Environmental Protection Agency (EPA).

- NNI has considered societal implications as an integral part of the process from the first year of the initiative. The National Nanotechnology Coordinating Office (NNCO) has been charged with monitoring potential risks, and the NSF is making support for social, ethical, and economic research an increasing priority in its funding.

- California has benefited substantially from federal nanotech funding, despite its failure to win one of the six NSF nanotech center awards in 2001. The state won more small tech grants in 2002 than any other, as well as the most Small Business Innovation Research and Small Business Technology Transfer awards for a three-year period. Even accounting for California's population and state economy, it has been highly successful at bringing federal dollars into its nanotech R&D.

- California does not have a comprehensive state nanotechnology R&D strategy comparable to the federal government's, but is well situated to become one of the first states to do so.

  Despite California's strengths, its position as nanotech leader is not secure. As the Executive Director of the NanoBusiness Alliance put it: "It's all there, but it's not working.

1.4 Impact of Nanotechnology

In the foregoing discussion, we have presented the underlying notions of nanotechnology by looking through the lens of two important areas of modern technological innovation. These two areas, biology and nanoelectronics together with their associated industries – medicine and computers and communications – are obvious arenas for the fruitful application of nanotechnology which undoubtedly will be strongly impacted by continuing advances.

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[10] Wolf, S., Quantum Information Science and Technology (QuIST), DARPA- DSO: http://www.darpa.mil/dso/thrust/math/quist.htm.

Beyond this point, assessing the scope of the subject becomes difficult, and in some ways this goes back to the language issue. For example, many have argued that much of chemistry and physics is already practiced at the nanoscale level, because these subjects are concerned with atoms, molecules and their various condensed phases. Ultimately, the subject of nanotechnology may disappear as a separate discipline, because it seems likely to suffuse all of the physical, biological and engineering sciences but in the sense of a mode of practice rather than a unique field of study. After all, biology, medicine and electronic devices were studied well before the term nanotechnology was coined, and the new fields of nanobiology, nanomedicine and nanoelectronics are just an extension of previous practice with an emphasis on a finer length scale with greater precision.[11]

Thus, in attempting to assess the implications of the subject, it is important not to confuse the penetration of nanotechnology, which will probably be universal as far as the scientific and engineering disciplines are concerned, with the impact of nanotechnology which will clearly be much more important in some areas than others. In some areas, we can expect hybrid structures, in which a nanomaterial with superior properties such as strength or electromagnetic shielding is blended with conventional polymers to give a composite with enhanced performance. Carbon nanotubes possess excellent thermal conductivity and conduction, and can be incorporated into materials and devices where heat sinks and the dissipation of static electricity is important. [12]

In this chapter, we shall not attempt an exhaustive list of the scope of the implications of nanotechnology, and it is unlikely that such a list could be compiled with much certainty at this time. On the other hand, the subjects that will profit from developments in nanotechnology are fairly easy to define in terms of the foregoing discussion. Any subject that depends on atomic or molecular precision for its practice, particularly as this relates to materials or devices, stands to profit from the subject of nanotechnology. Thus we leave breadth of impact as a question: which industries would like more precision and control in the manufacture of materials and devices? The list seems likely to be quite long, particularly within California.

The development of nanotechnology is occurring across a broad range of institutions including universities, national laboratories, and small and large companies. As the applications succeed, there will be an immediate effect that is expected to span the whole economy, but particularly the high technology sector. While the flow of capital will drive the development of nanotechnologies, it is important to initiate methods for the classification of these new materials in terms of their ecological impacts. As yet, there is no evidence to suggest that nanomaterials will differ in toxicity from their macroscale counterparts.[13, 14, 15]

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11 Nanoscience and Nanotechnology: Shaping Biomedical Research, in BECON Nanoscience and Nanotechnology Symposium Report. June 2000, National Institutes of Health: http://grants.nih.gov/grants/becon/becon_symposia.htm.

12 Fink, Uwe, et al., Nanoscale Chemicals and Materials-An Overview on Technology, Products and Applications. December 2002: http://scup.sric.sri.com/Enframe/Report.html?report=NANOT000&show=Navigation.html.

13 The Societal Implications of Nanotechnology, in Committee on Science U.S. House of Representatives. April 9, 2003: http://www.house.gov/science/hearings/full03/apr09/charter.htm.

14 Tringe, Heidi Mohlman and Jeff Donald, More research on societal and ethical impacts of Nanotechnology is needed to avoid backlash; experts say H.R. 766 is "CENTRAL" to GOAL. 2003: http://www.house.gov/science/press/108/108-049.htm.

15 Arnall, A. H., Future Technologies, Today's Choices. 2003, Greenpeace Environmental Trust: http://www.greenpeace.org.uk/MultimediaFiles/Live/FullReport/5886.pdf.

Almost every leading university in the country now offers a program in some aspect of nanotechnology and soon every scientist and engineer will be required to demonstrate the ability to work at the molecular level as a basic skill. Thus, the role of education and training is key for maintaining leadership in the forthcoming decades of nanotechnology. The rapid growth of information technology saw a steep rise in the influx of skilled software engineers into the U.S. from around the world. Currently, there is a possibility that the European Union will begin attracting skilled personnel from the United States.[16]

> SOON EVERY SCIENTIST AND ENGINEER WILL BE REQUIRED TO DEMONSTRATE THE ABILITY TO WORK AT THE MOLECULAR LEVEL AS A BASIC SKILL.

It has often been suggested that nanotechnology has been oversold. However, without a vision for the direction of the field, it is impossible to develop policy. A policy for industrial development with the strategy clearly marked in terms of the short-term and long-term goals of nanotechnology will greatly help to capitalize on the fruits of this field of research. Currently, nanotechnology is in a nascent phase and is experiencing explosive growth and this makes an organizing blueprint at the state level very timely. In California, research in nanotechnology is centered at certain academic campuses, a few of the high technology industries, national laboratories and many small business initiatives. A vision at the state level will help to forge an alliance between these entities and allow the state to maintain its economic and technological supremacy in the field of nanotechnology.[17]

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16 Williams, S. R., Testimony of R. Stanley Williams before the U.S. Senate. 2002: http://www.senate.gov/~commerce/hearings/091702williams.pdf.

17 DeVol, Ross C., Rob Koepp, and Frank Fogelbach, State Technology and Science Index. Comparing and Contrasting California. September 2002, Milken Institute: http://www.milkeninstitute.org/publications/publications.taf?functions=detail&ID=163&cat=ResRep.

CHAPTER 2: FORMATION AND TRANSFORMATION OF INDUSTRIES: NANOTECHNOLOGY

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Key Points in this Chapter:

In the next 5 to 10 years...

Nanotechnology industry clusters will form in California

- Industry clusters will form around key researcher/entrepreneur networks close to major research universities
- The global patenting rate of nanotechnology discoveries will accelerate

In the next 10 to 20 years...

Mature industry clusters will be established

- Existing nanotech industry will be concentrated in regions with established networks, and research and economic infrastructure
- New start-up companies will dispassionately compare California's workforce, policies, and business costs with foreign sites when deciding where to base their design and production centers

2.1 Introduction

Output per worker, real wages, and the standard of living grow over long periods of time at a rate equal to the sum of the growth in human capital per worker and pure technological progress. Human capital grows primarily through increased years of education, but also through higher quality education and increased on-the-job training. Pure technological progress reflects our growing abilities as a nation to produce more from given resources and to produce new valuable goods and services which were previously impossible.[1]

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[1] There is in fact some overlap between human capital growth and technological progress resulting from the fact that as we accumulate more knowledge, our students learn how to do things that were previously unknown. This interaction effect raises issues for growth accounting which need not concern us for the present discussion.

Technological progress reflects the commercial use of a stream of innovations created by scientists and engineers, entrepreneurs and executives, artists and designers, mechanics and tinkerers. Although creativity is widespread in our population – and we can draw on innovations from abroad – it is remarkable that technological progress at any given time is highly concentrated in a relatively few firms in a few industries (Harberger 1998, Darby and Zucker 2003a). These few firms undergo metamorphic progress which dramatically transforms existing industries, forms new industries, or both. It is misleading to concentrate on the many firms in many industries achieving perfective progress through gradual improvement or inching up. To understand or affect technological progress we must focus on the exceptions – the industries and firms achieving metamorphic progress.

The industries undergoing metamorphic growth vary over time. Famous examples from the past include spinning, weaving, steel, glass, and aircraft. More current examples would be semiconductors, information technology, and biotechnology. The source of the driving innovations for metamorphic change may be internal or external to the industry, with external innovations using different technological bases, the most threatening to existing firms in a transforming industry (Tushman and Anderson 1986).

In this chapter, we report preliminary results from an ongoing study of an emerging area of metamorphic progress – nanotechnology. For purposes of comparison, we will refer to biotechnology which is a well-studied recent and ongoing case of science-driven metamorphic progress which formed and transformed industries. In both cases, breakthrough academic discoveries have played or are playing a major role, but the close collaboration among academic and industrial innovators strengthens and accelerates the work in both science and commerce – a virtuous circle (Zucker and Darby 1995, 1996).

The next section recounts the explosive growth of publishing and patenting in nanoscale science and engineering and compares that growth to biotechnology at a similar scale of development. Section 2.2 demonstrates the high degree of geographic concentration exhibited by the science base for nanotechnology. In section 2.3, we present preliminary evidence on where firms are entering into nanotechnology, what kinds of technologies they are involved in, and the extent to which they are working with firms. The final section of the chapter presents a summary of the evidence and our conclusions.

2.2 An Explosion of Nanoscale Science and Engineering

The U.S. government has identified nano S&T as a scientific and technological opportunity of immense potential, formally launching a National Nanotechnology Initiative (NNI) in January 2000. It is extremely difficult to define simply the full range of nano S&T, but the NNI's steering committee settled on the following definition of nanotechnology:

> Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1 - 100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size. The novel and differentiating properties and functions are developed at a critical length scale of matter typically under 100 nm. Nanotechnology research and development includes manipulation under control of the nanoscale structures and their integration into larger material components, systems and architectures. Within these larger scale assemblies, the control and construction of their structures and components remains at the nanometer scale. In some particular cases, the critical length

scale for novel properties and phenomena may be under 1 nm (e.g., manipulation of atoms at ~0.1 nm) or be larger than 100 nm (e.g., nanoparticle reinforced polymers have the unique feature at ~ 200-300 nm as a function of the local bridges or bonds between the nano particles and the polymer).[2]

Roco, Williams, and Alivisatos (1999), Roco (2001), and Roco and Bainbridge (2001) provide a thorough review of the present state of nano S&T, the implementation of the NNI, and an introduction to thinking about the implications of nano S&T for our economy and society.

Like the actress who is an "overnight star" after years of hard, unnoticed work, nano S&T has burst upon the science and engineering scene a bit less suddenly than one would judge by the current notices. In terms of publications, rapid growth began about 1990 as shown by Figure 2.1. This figure reports data which we obtained by searching on the topic "nano*" by year in the Science Citation Index Expanded for May 30, 2003 (Institute for Scientific Information 2003). The 1981-1990 values (averaging one third article per thousand) reflect some substantial early scientific work as well as the background error in the search strategy. These values show no trend and none except 1990 are significantly different from their mean. Since 1990, the growth in nano S&T articles has been remarkable, and now exceeds 2 percent of all science and engineering articles.[3] We are developing a better algorithm for computer identification of nano S&T articles, but the current method identifies about one third of the articles in the Virtual Journal of Nanoscale Science & Technology (hereafter, *VJNano*), which suggests that nano S&T accounts for about 6 percent of all scientific and engineering articles.[4]

Nano S&T has burst upon the science and engineering scene a bit less suddenly than one would judge by the current notices.

Since 1990, the growth in nano S&T articles has been remarkable, and now exceeds two percent of all science and engineering articles.

The patent data suggest a takeoff date for nano S&T some five years earlier than 1990. Figure 2.2 presents data on patents granted by October 7, 2003 containing the string "nano" in their title or abstract.[5] The data is presented for two different dating conventions: by year the patent was granted and by the year the patent was applied for. The latter is more precise in terms of when the invention was actually made (typically about 3 months before the date of application), but suffers from right-truncation bias which is increasingly significant over the last four or five or six years of data. Some patents applied for before 2000 were still pending on October 7, 2003, as were many of those applied for in 2000-2002 and all applied for in 2003. If we allow for a lag between application

2 Subcommittee on Nanoscale Science, Engineering and Technology (NSET), Committee on Technology, National Science and Technology Council, February 2000, as posted at http://nano.gov/omb_nifty50.htm.

3 Beginning in 1990, the counts of nano articles per 1000 S&E articles was significantly greater than the 1981-1989 mean and increasing every year.

4 *VJNano* began publication at the beginning of 2000 and attempts to identify articles in other journals which report on nano S&T research.

5 To be precise, the underlying data were obtained by searching the USPTO Patent Full-Text and Image Database (at http://164.195.100.11/netahtml/search-bool.html) on October 13, 2003. The 2003 counts were annualized by multiplying by 365/280.

and grant dates (25 months was the mean difference for 1981-2000), both series tell the same story. Patents applied for 1976-1985 and granted 1976-1986 had mean values of 37.4 and 33.3 patents per year and no observation within these periods differed from the respective means by as much as two standard deviations. Patent growth takes off in 1986: No number of patents applied for after 1985 (excluding the severely truncated 2002-2003 observations) nor granted after 1986 were within two standard deviations of the cited means.

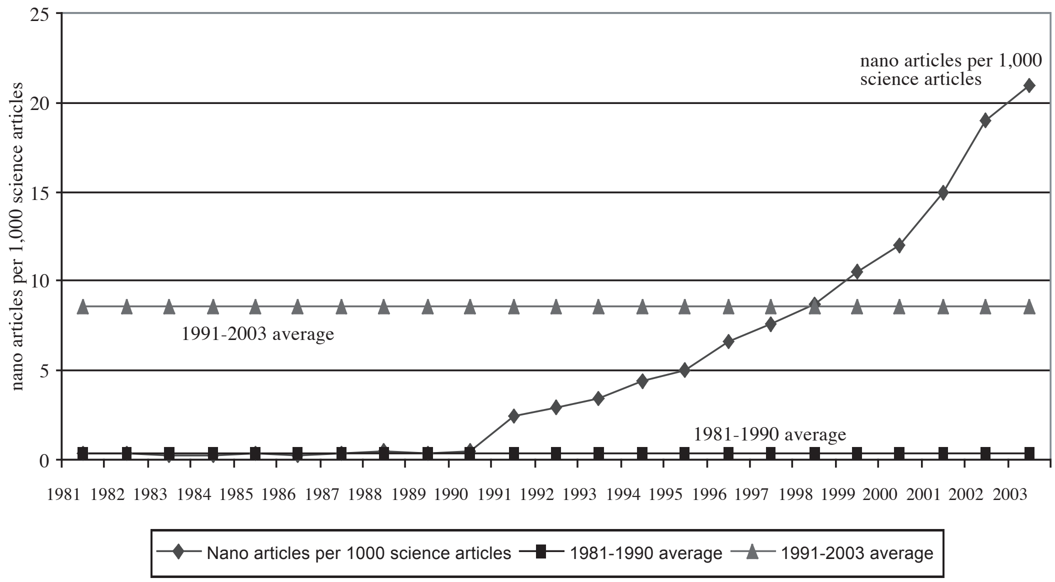


Figure 2.1: Nano Articles per 1000 Science Articles
Source: ISI Web of Science (Updated to May 30, 2003. 2003 data are (365/150)* totals for January 1-May 30, 2003.)

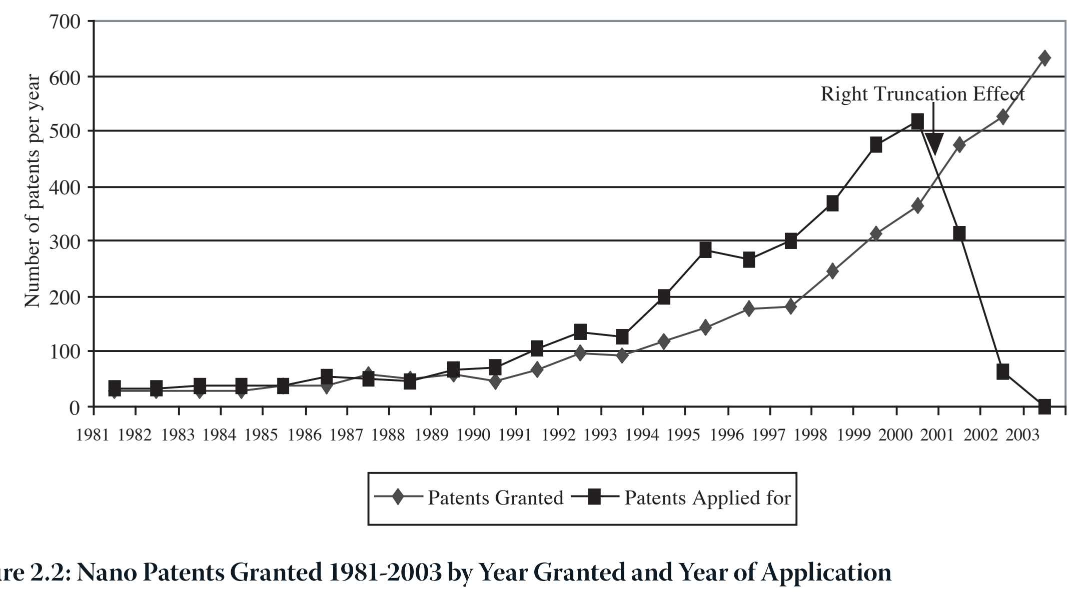
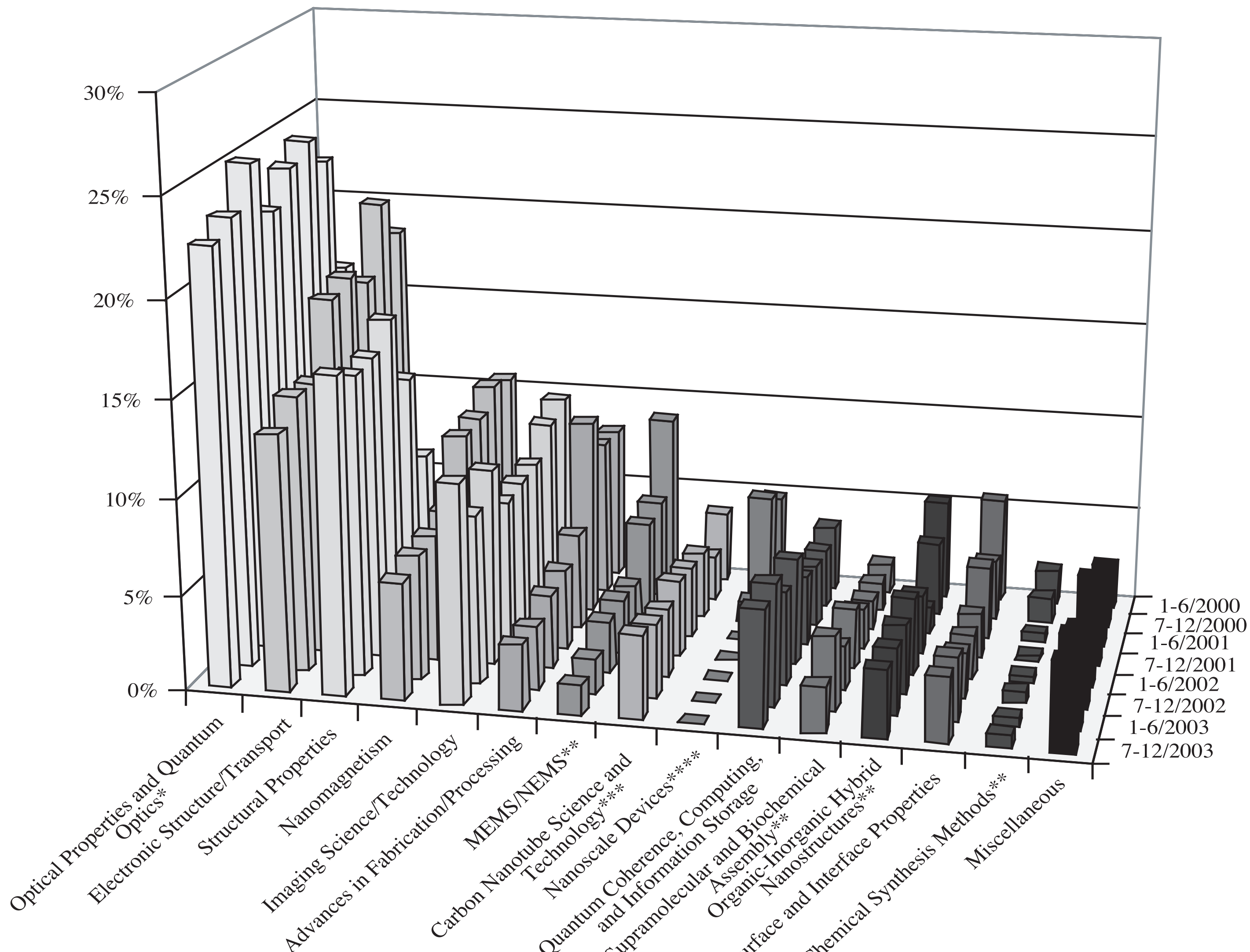


Figure 2.2: Nano Patents Granted 1981-2003 by Year Granted and Year of Application

Figure 2.3 illustrates the breadth of nano S&T by showing the distribution of articles in *VJNano* by classification and volume. We should note that *VJNano* is a publication of the American Institute



*In 1(1-2): Nanooptics and Quantum Optics.
**First used in 1(2 or 3).
***First used in 3(8).
****Dropped in 3(7).

Figure 2.3: Percentage Distribution of *Virtual Journal of Nanoscale Science & Technology* Articles by Classification, Data from Volumes 1-8, January 2000-December 2003

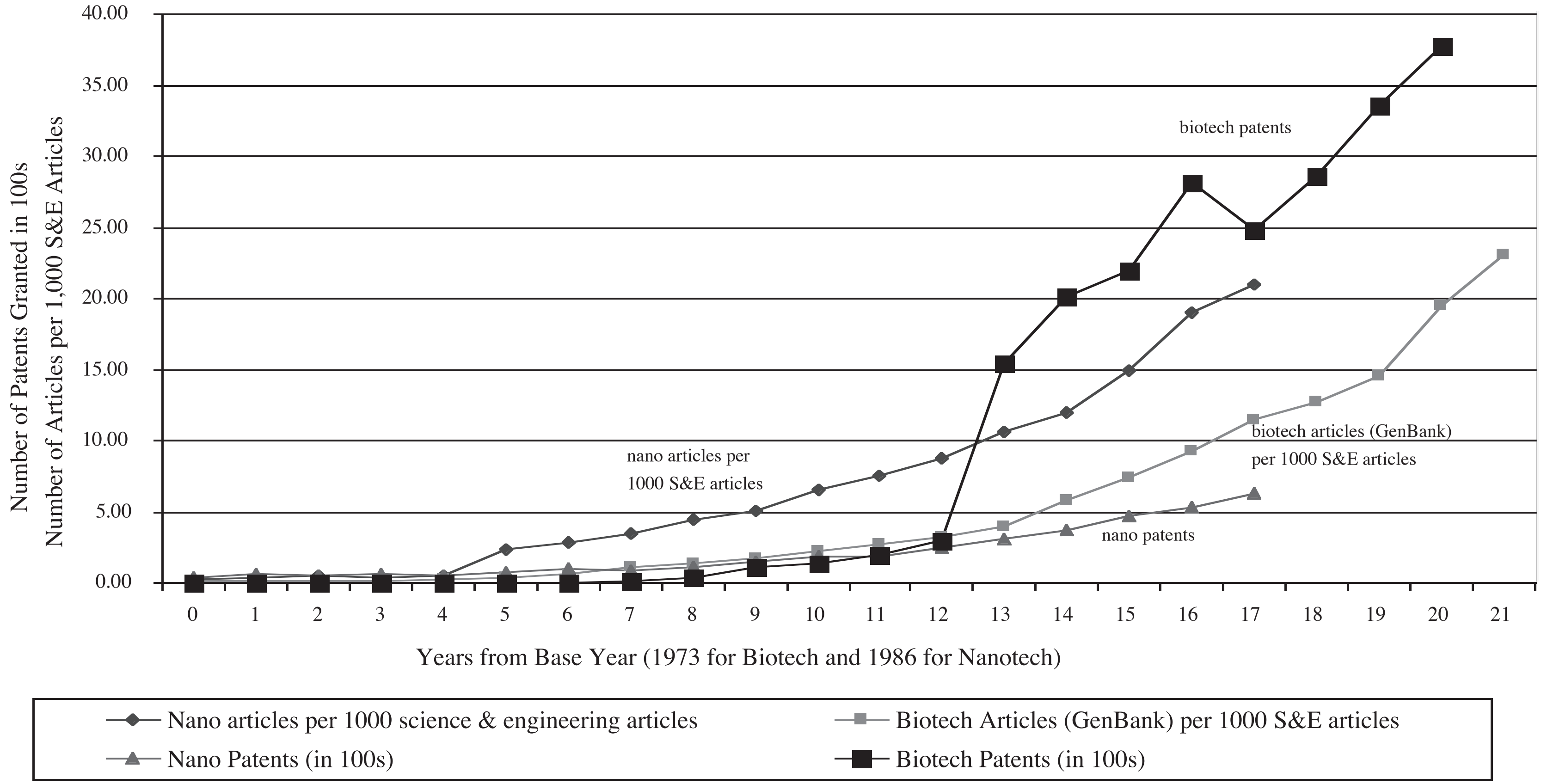


Figure 2.4: Nanotech and Biotech Publishing and Patenting Compared 1973-1994 for Biotech and 1986-2003 for Nanotech

of Physics and American Physical Society and that the intersection between biotechnology and nanotechnology may be underrepresented among these classifications.

Comparing Nanotechnology and Biotechnology

In order to compare nanotechnology and biotechnology at similar stages of development, we need to determine a base year for the start of the technology. The Cohen-Boyer invention of genetic engineering (recombinant DNA) in 1973 is the conventional base year for biotechnology.[6] There is no consensus yet on the starting date for nanotechnology, but based on the years when publishing and patenting took off, we will tentatively use 1986 as the base year. Interestingly, the atomic force microscope (AFM) was invented in 1986 by Binnig, Calvin Quate, and Christoph Gerber (1986); the AFM greatly broadened the range of materials which could be viewed at the atomic scale and enhanced the ability to manipulate individual atoms and molecules.[7] Haberle, Horber, and Binnig (1991) report a modified AFM for use on living cells with which they observed the effects of antibody attachment and changes in salinity on living red blood cells. Darby and Zucker (2003b) argue that such inventions of procedures or instruments – not the paradigm shifts famous from Kuhn (1962) – are the usual "inventions of a method of inventing" which set off major scientific and industrial transformations.[8]

> TAKEN AS A WHOLE, THE SCIENTIFIC AND PATENTING GROWTH OF NANOTECHNOLOGY IS OF AT LEAST THE SAME ORDER OF MAGNITUDE AS BIOTECHNOLOGY AT A SIMILAR STAGE OF DEVELOPMENT.

Figure 2.4 compares the remarkable increase in publishing and patenting that occurred during the first twenty years of the biotechnology revolution with what is occurring now in nano S&T. For articles, nano S&T is maintaining a growing lead over biotechnology articles. Recall that we so far identify nano articles as simply those that include the string "nano" in the ISI topic search, and for the overlap period 2000-May 2003, this search identifies only a third of the articles identified in *VJNano*. Biotech articles are defined in the figure as any that report a genetic sequence discovery (i.e., appear in GenBank), and this definition is also conceptually overly narrow, but it has been proven in practice a very useful measure in our work on biotech.

Nano S&T patents were ahead of biotech patents early in the process (through year 10) because practically none were issued in biotech until the courts gave the go ahead in 1980. Thirteen years into the biotech revolution (1986), biotech patenting took off as: (a) gene sequences were patented

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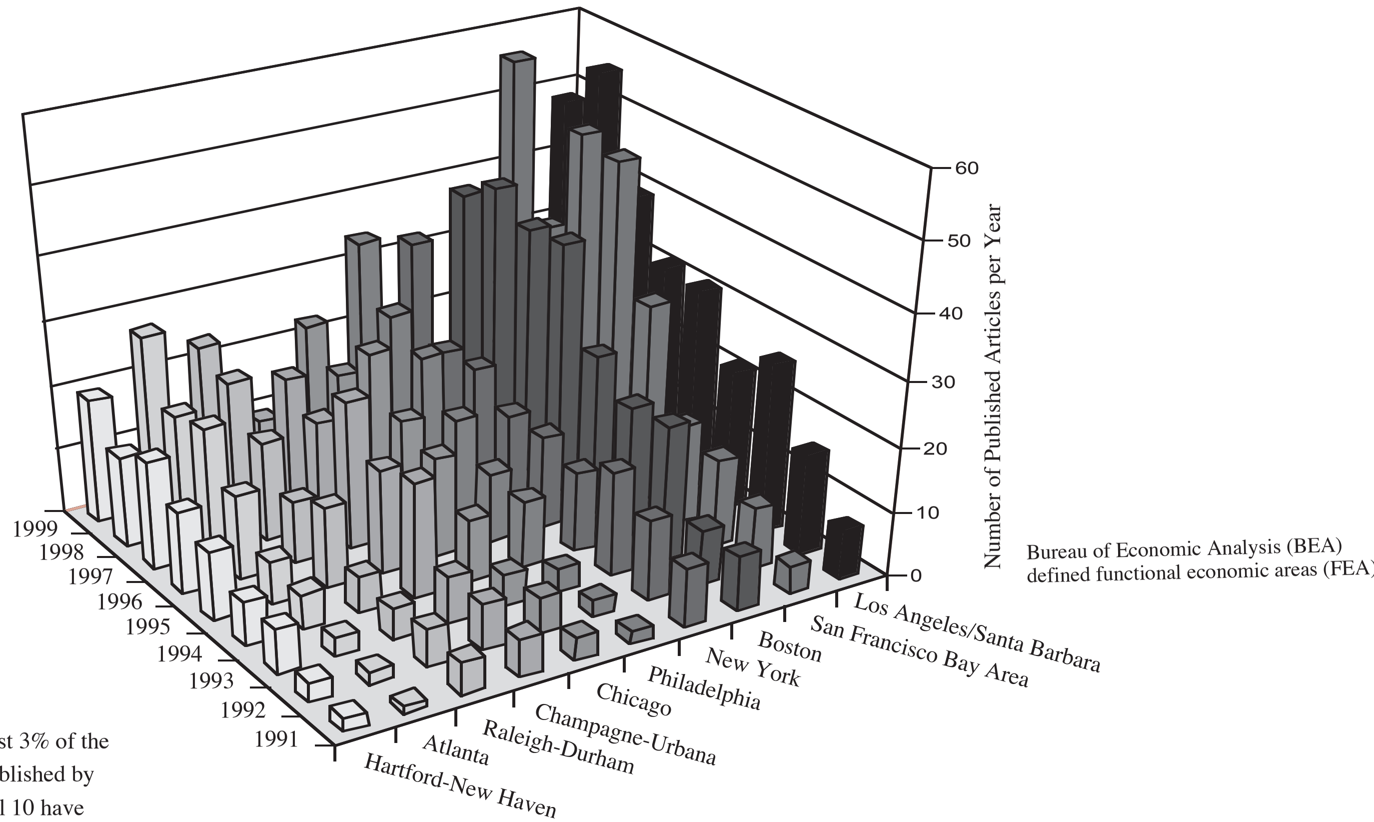
6 Cohen, Chang, Boyer, and Helling (1973) and Cohen and Boyer (1980).

7 The scanning tunneling microscope (STM) was the first instrument to enable scientists to obtain atomic-scale images and ultimately to manipulate individual atoms on the surfaces of materials. It was invented in 1981 at IBM's Zurich Research Laboratory and reported by the inventors Gerd Karl Binnig and Heinrich Rohrer (1982 and 1983); they received the Nobel Prize in Physics in 1986 for their STM work. The STM works by moving a very fine pointer back and forth over a surface with each scan line displaced slightly from the next. A sensitive feedback mechanism maintains a constant distance relative to the surface so that a three dimensional representation is obtained. The procedure is called raster scanning in reference to the parallel lines which make up a television picture and is the basis for scanning probe microscopy, including the AFM. The STM could be used only on conductive materials (metals) due to the electron tunneling method used to maintain the constant distance between pointer and surface.

8 Zvi Griliches (1957a, 1957b) was the first economist to study the class of breakthrough discoveries which he named an "invention of a method of inventing." His case was hybrid seed corn, a method of breeding superior corn for specific localities that effectively excluded farmers from reproducing the hybrid seed by saving part of their crop.



Each FEA plotted has at least 3% of the 1991-99 US total articles published by top research universities, All 10 have 58% of this total.

Figure.2.5: All Sciences and Engineering, 1991-1999, by Region Nano Articles with Authors at Top-112 Research Universities

with little proof of their use and (b) many variations on drug candidates were patented in an attempt to prevent quick competition from me-too drugs if one particular candidate was proven safe and effective.

Taken as a whole, the scientific and patenting growth of nanotechnology is of at least the same order of magnitude as biotechnology at a similar stage of development.

2.3 Geographic Concentration of the Science Base for Nanotechnology

Just as metamorphic technological progress is concentrated in relatively few firms in relatively few industries, there is also a concentration of knowledge in a few scientists and engineers who are pushing the frontiers of nano S&T and in the laboratories in which they work. This concentration is a notable characteristic of previous scientific breakthroughs, especially those which involve a significant degree of tacit knowledge – art learned by doing at the lab bench level. This tacit knowledge provides a natural excludability which limits the diffusion of the new knowledge in cooperation with or even in the absence of explicit intellectual property rights of the discovering scientists and their organizations.[9]

We are able to illustrate the geographic distribution of the science base for nano S&T by reference to the U.S. University Indicators of the Institute for Scientific Information®, Inc. (2000b) database which we have licensed for prior research. This database contains all the ISI indexed-articles from 1981 through 1999 with one or more authors in one of the top-112 U.S. research universities as identified by the Institute for Scientific Information.[10] Since this database lacks the ISI topics (keywords) data field, the definition of "nano article" switches for the rest of this chapter to those articles which have the string "nano" in their title.

Figure 2.5 illustrates the distribution of the science base for nanotechnology based on the number of nano articles with an author(s) in a top-112 research universities. If more than one top-112 research university is represented among the authors' affiliations, we count 1/n article for each such affiliation where n is the number of different top-112 research university for the article. We then total for each region the counts at each of the top-112 research universities it contains. Ten regions (out of 183 functional economic areas identified by the U.S. Bureau of Economic Analysis) account for 58 percent of the articles with any top-112 university authors, and over 28 percent of all top-112-university nano articles is accounted for by the Los Angeles-Santa Barbara, San Francisco Bay, and Boston regions.[11] Note also that these 10 regions – Los Angeles-Santa Barbara, San Francisco Bay, Boston, New York City, Philadelphia, Chicago, Champagne-Urbana, Raleigh-Durham, Atlanta, and Hartford-New Haven – are notable for the strength in nano S&T of particular academic institutions and are not predictable by size, economy, or even overall strength of the science base.[12] The Los Angeles-Santa Barbara and San Francisco Bay regions alone account for 19.58 percent of all top-112-university nano articles, with the other six California regions adding only 0.18 percent to this total.[13]

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[9] See Zucker, Darby, and Brewer (1998) and Zucker, Darby, and Armstrong (1998, 2002).

[10] The ISI definition is based upon federal research funding amounts. California, for example, has 12 top-112 universities: Caltech, Stanford, USC, and the nine campuses of the University of California.

[11] The top-20 and top-30 regions account for 82 and 94.5 percent, respectively, of the articles with any top-112 university authors.

[12] Compare these regions, for example, with the relative importance of high-tech states in Darby and Zucker (1999) and Zucker and Darby (1999).

[13] Ten of California's twelve top-112 universities are located in the Los Angeles-Santa Barbara and San Francisco Bay regions. UC Davis and UC San Diego are located in the Sacramento and San Diego regions, respectively.

The earliest nanotechnology commercial applications have been concentrated in semiconductors and advanced materials. Griliches (1957a, 1957b) argued that the earliest applications of an invention of a method of inventing are to those areas with the greatest expected profitability – now known as the lowest-hanging fruit. Klevorick, Levin, Nelson, and Winter (1992) have rightly emphasized that profitability is based on the appropriability of returns by the pioneer(s) as well as upon technological opportunity.

The low-lying-fruit theory suggests focusing for analysis of early industrial formation and transformation on the regions with the strongest science bases in the areas most relevant to semiconductors and advanced materials. We do this in Figure 2.6. We calculate the data reported in Figure 2.6 by starting with the same articles plotted in Figure 2.5, but then restrict the count to only that subset of nano articles by authors at top-112 research universities in the science and engineering journals most relevant to semiconductors and advanced materials. We define those fields – using ISI classifications – as: Applied Physics/Condensed Matter/Material Science; Electrical & Electronic Engineering; Mechanical Engineering; Metallurgy; Materials Science and Engineering; Optics & Acoustics; Physics; and Spectroscopy/Instrumentation/Analytical Science.[14] We see that the pattern of publication of nano articles by authors at top-112 universities in this subset of journals is very similar to that for all their nano articles: The only shift in regions included in the top 10 is that the Hartford-New Haven region slips out (to 11th place) and the Binghamton-Elmira, NY region (13th for all nano articles) replaces it at 10th place. A more subtle change is that the science base is somewhat less concentrated: The top-3, top-10, top-20, and top-30 regions account for 23, 48, 69, and 82 percent, respectively, of the total for nano articles with any top-112 university authors and from this restricted set of fields, compared to 28, 58, 82 and 94.5 percent for nano articles with any top-112 university authors in all science and engineering fields.

The lead is smaller for the very fields with the most immediate application to industry, suggesting that California cannot afford to sit on its scientific laurels and expect to be the big winner in nanotechnology.

California has a powerful lead in the science and engineering base for nanotechnology, and this provides hope that a disproportionate share of the metamorphic progress due to the nanotech revolution will be concentrated in California. However, the lead is smaller for the very fields with the most immediate application to industry, suggesting that California cannot afford to sit on its scientific laurels and expect to be the big winner in nanotechnology.

2.4 Firm Entry into Nanotechnology

There is in fact no census or widely accepted database to consult as to which firms are actively using nanotechnology in production or at least R&D activities. We will construct a public database – NanoBank.org – over the next several years aimed at filling that and other information gaps faced by both researchers in nano S&T and those who study their impact.[15] For now, the large

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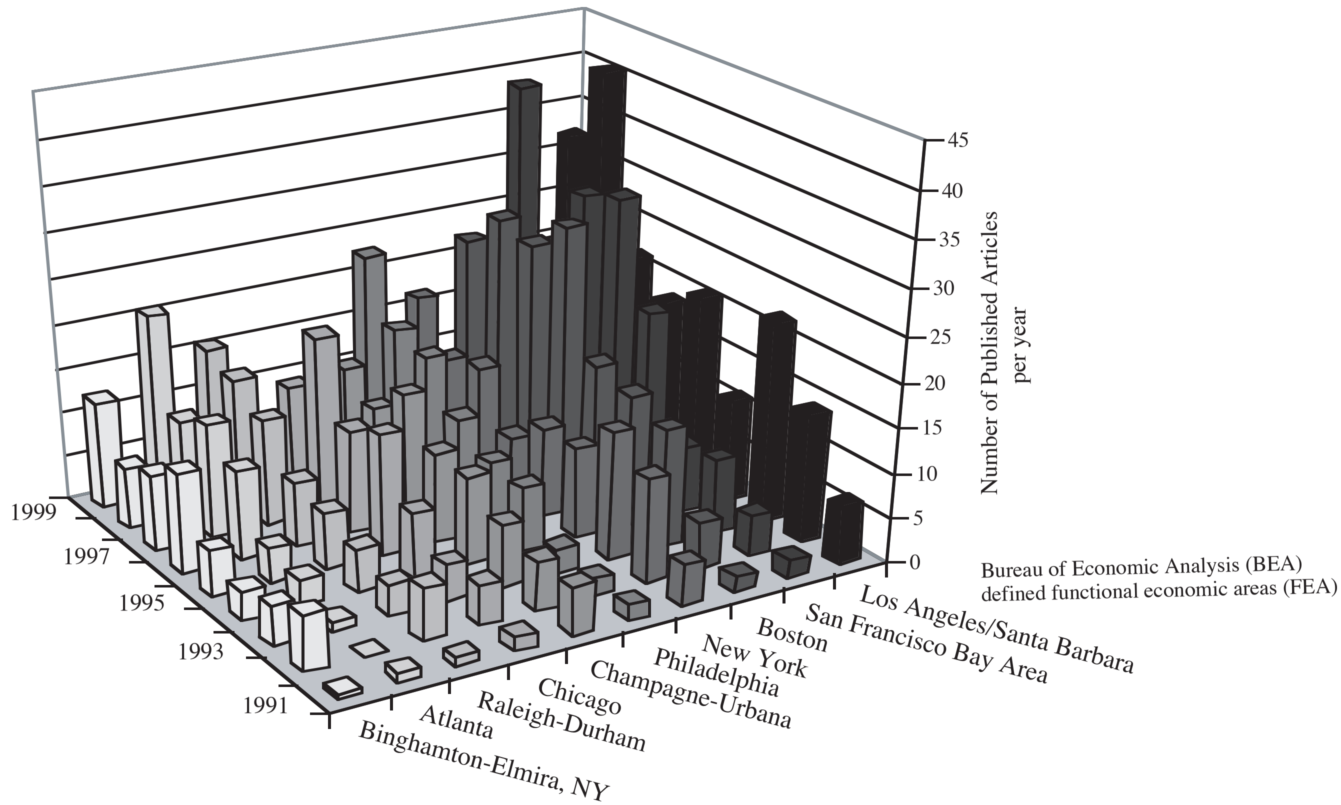
[14] See Darby and Zucker (1999) for a discussion of mapping science base to industry clusters.

[15] NanoBank.org is being constructed under a National Science Foundation Nanoscale Interdisciplinary Research Team (NIRT) award SES-0304727 by Principal Investigators Lynne G. Zucker, Michael R. Darby, Roy Doumani, Jonathan Furner, and Evelyn L. Hu.



Each FEA plotted has at least 2.6% of the 1991-99 US total articles published by top research universities, All ten have 48% of this total.

*ISI Journal Classifications: Applied Physics/Condensed Matter/Material Science; Electrical & Electronic Engineering; Mechanical Engineering; Metallurgy; Materials Science and Engineering; Optics & Acoustics; Physics; and Spectroscopy/Instrumentation/Analytical Science

Figure 2.6: Science & Engineering Most Relevant to Semiconductors & Advanced Materials* Nano Articles with Authors at Top-112 Research Universities, 1991-1999

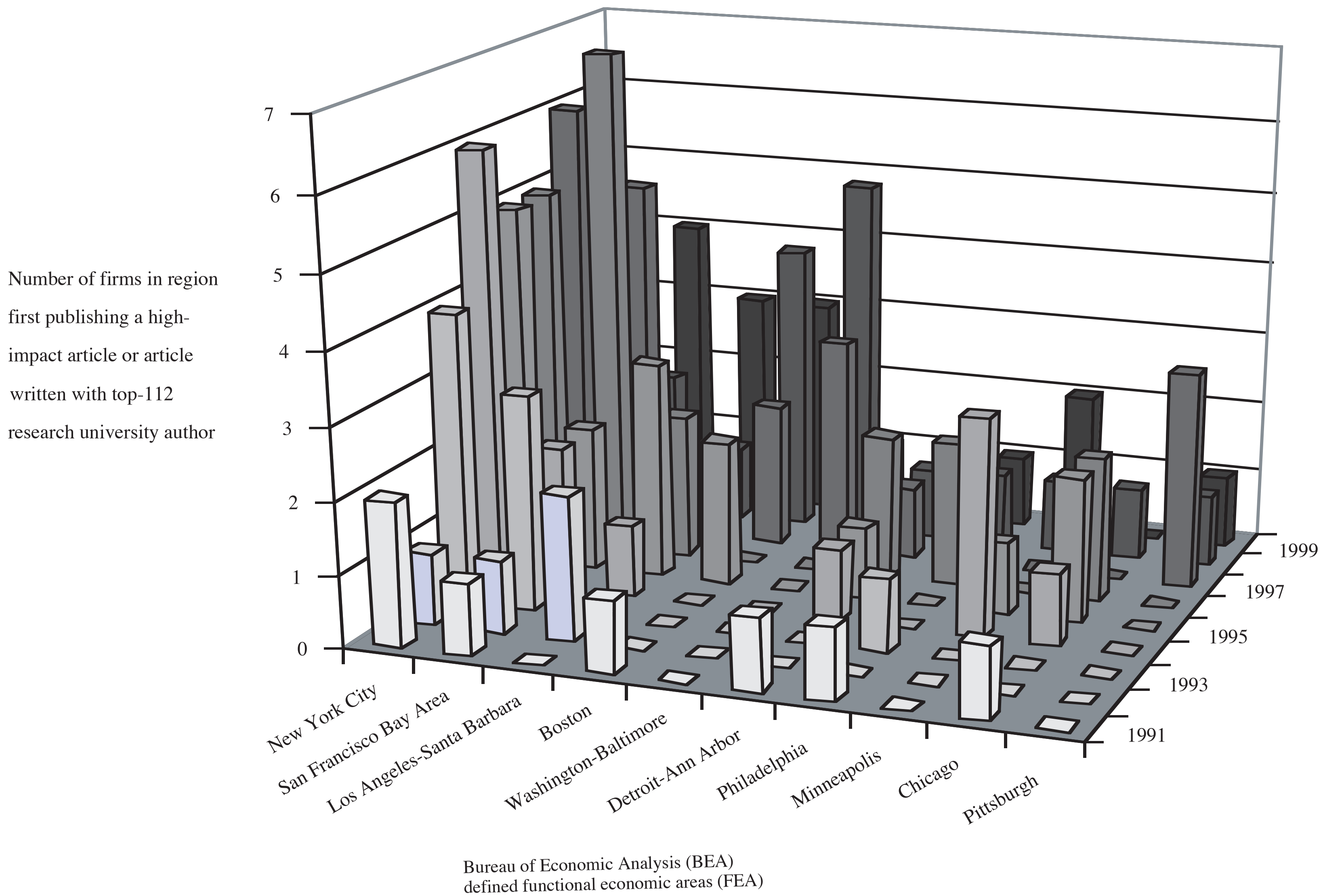


Figure 2.7: Firm Nanotech Entry by Region and Year, 1991-1999

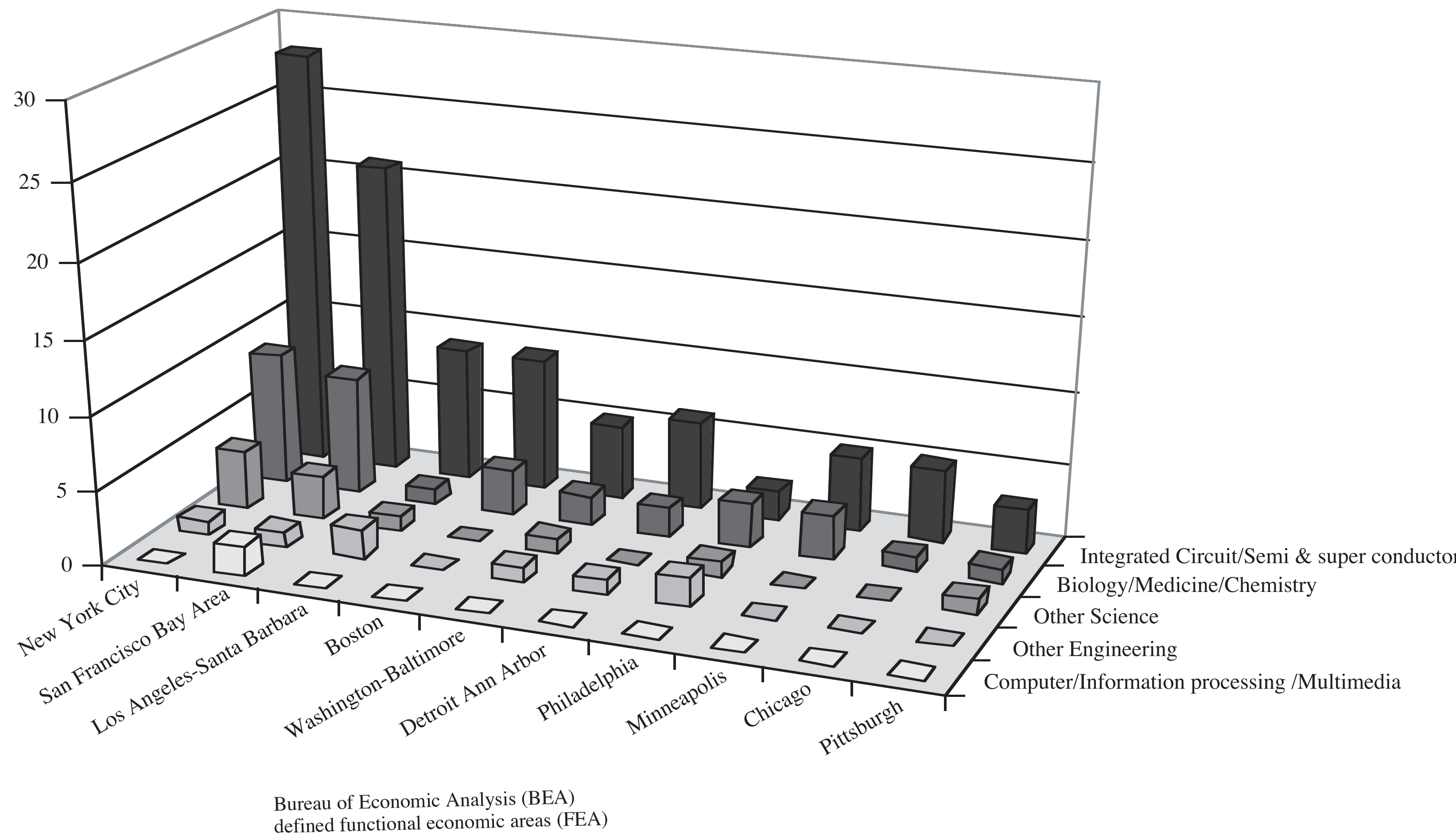
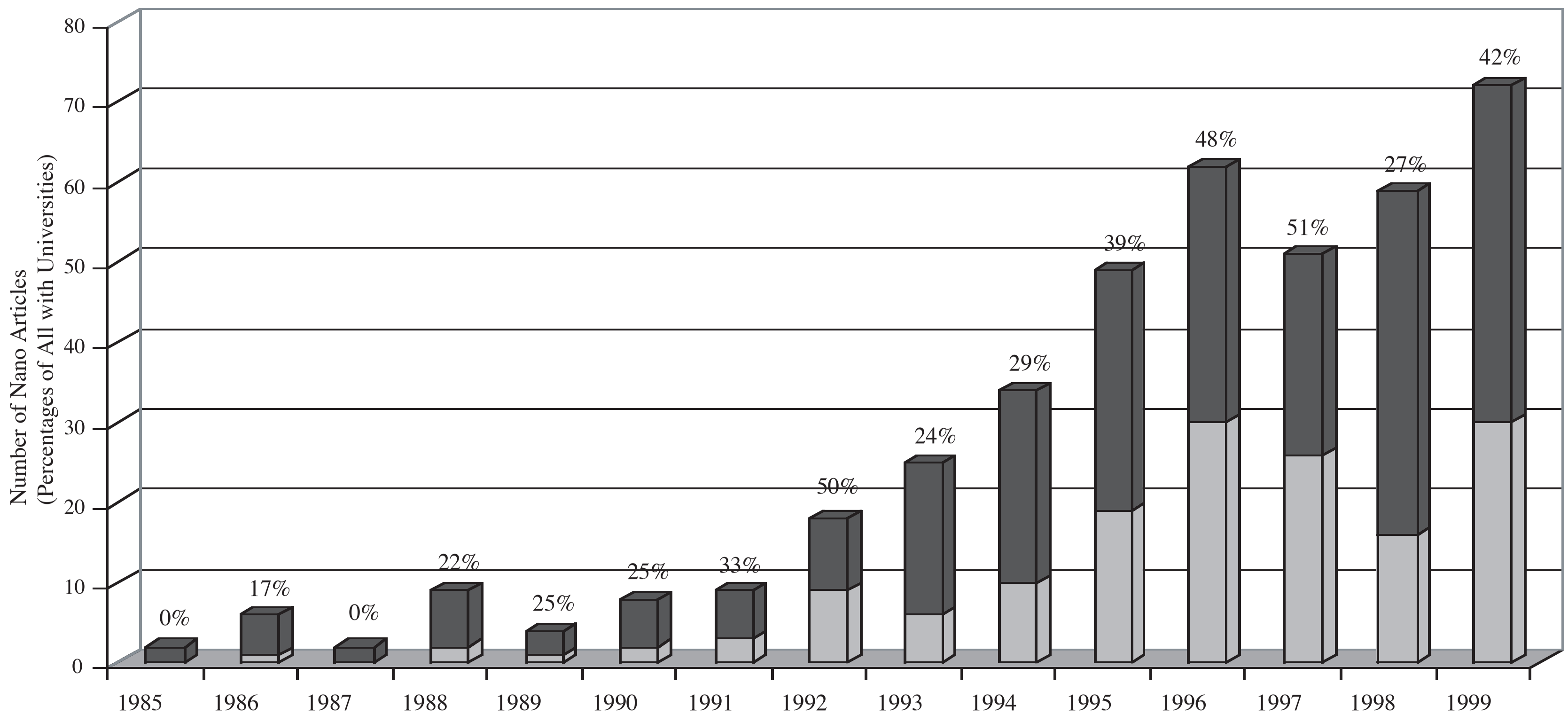


Figure 2.8: Firm Nanotech Entry by Region & Science-Technology Area, Entry Measured by Publication of a High-Impact Article and/or Article with a Top-112 University Author



Note: In California, the 9 University of California campuses, Caltech, Stanford, and USC are Top-112 universities. The figure is for all nano articles with an author from California and an author (possibly the same) affiliated with a firm.

Firm articles with top-112 research universities | Firm articles not with top-112 research universities

Figure 2.9: California NanoArticles with Authors in Firms by Year and Top-112 University Co-authorships

number of articles in the top-112 universities and/or High-Impact databases provides a means of identifying firms with a sufficiently deep involvement to be either publishing highly cited research articles or articles co-authored with professors from top-112 universities or both. Based on the patterns observed in biotechnology, few other firms without such ties are likely to become significant players.

Figure 2.7 illustrates the number of firms first publishing in the top-112 universities or the High-Impact Papers (Institute for Scientific Information 2000c) databases by region and publication year with the firm's region based upon the address given by the author at the firm. High-Impact Papers are defined by ISI as papers that are highly cited in the year of publication and the following year. The regions where firms are entering overlap with the regions where top-112-university articles are being written, except that Washington-Baltimore, Detroit-Ann Arbor, and Pittsburgh appear in the top 10 regions for firm entry. Darby and Zucker (2003b) show that in a multiple-poisson-regression context, both the number of highly cited articles published in a region and its average wage level (a measure of labor-force quality) are significant determinants of where and when firms enter nanotechnology. The effects of federal research funding to and nano articles by authors from top-112 research universities, regional employment, and total venture-capital flows are not statistically significant when all of these variables are entered in the same poisson regression, although these variables may be significant in regressions in which they are not competing with High-Impact articles and/or average wages. It is difficult, with small samples, to measure separate effects of highly correlated variables such as high-impact articles (mostly authored by faculty with large federal research funding) and the amount of federal research funding. We expect some additional variables will be significant in future research when we can identify additional firms entering nanotechnology. The statistical insignificance of past venture capital flows is consistent with efficiency in that market.

> STAR SCIENTIST AUTHORSHIPS OF ARTICLES AS OR WITH EMPLOYEES OF A FIRM WERE A POTENT PREDICTOR OF THE EVENTUAL SUCCESS OF BIOTECH FIRMS.

Figure 2.8 shows that the science base fields where firms are publishing are concentrated in those fields which are relevant to semiconductors and advanced materials and, to a lesser extent, to the biomedical and chemical industries. Other articles are sparsely distributed across other fields of science and engineering.

> CALIFORNIA IS EVEN BETTER SITUATED THAN FOR BIOTECHNOLOGY TO BE THE LEADING STATE IN ADOPTING AND BENEFITING FROM THE NANOTECHNOLOGY REVOLUTION.

Star scientist authorships of articles as or with employees of a firm were a potent predictor of the eventual success of biotech firms and Zucker, Darby, and Armstrong (2002) showed that counts of articles authored by firm employees with authors at top-112 universities had a significant (although smaller) impact on firm success. For the state of California alone up through 1999, we have available not just the articles in the top-112 universities ISI database, but all articles published with an author's address in California.[16] So, for California, we can trace all nano articles published with one or more authors affiliated with a firm and which of these articles also has an

[16] This database is part of Institute for Scientific Information (2000a) database.

author at a top-112 university.[17] These article counts are summarized in Figure 2.9. We see not only extensive and increasing publishing by authors working in California for firms, but also that a rising percentage of these are written in collaboration with scientists and engineers at top-112 research universities (indicated in parentheses above each bar). The university-firm knowledge flows represented by these articles augur well for the success of California nanotechnology firms and for the vitality of nano S&T research at California's research universities.

2.5 Summary and Conclusions

Nanoscale science and technology has all the earmarks of the kind of breakthrough metamorphic progress in which cascades of important scientific discoveries create the technological opportunities which transform existing industries and create new ones. We can confidently expect nanotechnology to account for a significant proportion of technological progress and economic growth over the next several decades.

California is even better situated than for biotechnology to be the leading state in adopting and benefiting from the nanotechnology revolution. For nanotechnology, Southern California has a science and engineering base on a par with the San Francisco Bay Area and matched only by the Boston Area. Northern California is the center of early applications in semiconductors and biotechnology while Southern California also has great strength in biotechnology and the rapidly growing applications of medical devices and telecommunications.

While California has an exciting early lead, the race to apply nanotechnology to new products and services will be a long one. It will be a loss to the nation if California's recent fiscal and regulatory crises impair the sources of our success in biotechnology and early lead in nanotechnology: (a) great research universities supporting cutting edge faculty research and permitting those faculty to play leading roles in formation of new firms and technology transfer to existing firms, (b) a tax and regulatory climate which encourages entrepreneurs to form new firms and venture capitalists to finance those firms, and (c) a highly skilled population which believes in growth, progress, and the future. It is the people of California who have created the climate for growth and opportunity, dared to start most of the state's new enterprises and expand existing ones, and attracted other talented and creative people to join them in their adventure. While it is hard to see beyond the current financial cuts threatening the continued vitality of the University of California and a regulatory environment which has become more hostile to enterprise and growth, it is even harder to bet that the people of California will not work through the current problems and continue as leaders of America's technological progress.

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[17] We are working to generalize the star definition used in our biotechnology research to one applicable in science and engineering generally, and will report on this research later.

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CHAPTER 3: NANOTECHNOLOGY COMMERCIALIZATION BEST PRACTICES

Anthony A. Waitz
Quantum InsightSM

Key Points in this Chapter:

In the next 5 to 10 years...

Nanotechnology start-ups will struggle through initial obstacles

- Gaining intellectual property protection and obtaining funding may be even more difficult for nanotech than other emerging technologies
- The high cost of research & manufacturing equipment will restrict access to development and commercialization
- Government high-tech small business grants, loan programs and corporate investment in small firms can be critically helpful for early growth

In the next 10 to 20 years...

California's advantages could erode

- Aggressive patenting tactics may lead to litigation between companies that slows industry development
- Small companies with successful technologies partner with or are bought by large companies based outside California
- A shortage of trained workers and punitive environmental regulations may retard development in California

3.1 Introduction

In this chapter, we survey some of the key factors for success in nanotechnology commercialization. Our consulting firm, Quantum InsightSM, has had exposure to hundreds of nanotech startup companies. Our observations on successful and unsuccessful tactics and strategies come primarily from this exposure, which has been gleaned by working with venture capital (VC) firms, corporate VC groups, and startups in the area of nanotechnology. In looking at all these nanotech startup efforts, trends began to appear. For example, there are common strategies used by companies to gain VC funding, while other companies that were struggling with funding used different strategies. Our firm also works with large corporations that are making investments in the area of nanotechnology. From these engagements, we have seen the full spectrum of issues related to commercializing nanotechnology. The organization of this chapter is to first focus, in section 3.2, on issues that are specific to nanotechnology startups. The reason for this is that much commercialization of nanotechnology will be through this path. Secondly, we look at issues relevant to all nanotechnology commercialization in sections 3.3 and 3.4. Throughout we provide a good number of examples that illustrate the points being made. These examples come from both pure nanotech startups and other small-tech startups in areas such as MEMS (Micro Electro Mechanical Systems).

3.2 Phases of a Nanotech Startup

3.2.1 Inception

Common Strategies

In some industries, patents are not critical to business success – firms focus more on swift execution than on intellectual property (IP) protection. This is not the case for nanotech firms. IP has been a central issue to every nanotech startup that we have looked at. IP is such an important topic in the realm of nanotechnology commercialization that we devote section 3.4 of this chapter to discussing it. From our point of view, inception of a company is synonymous with the acquisition of the company's initial IP.

Licensing IP

Most commercialization efforts start with taking steps to protect IP through the filing of patents. Most patents in the area of nanotech are generated by either large companies, by universities or by government labs. Many startups in nanotechnology get at least their initial IP from universities or government labs. Some of the California based government labs/agencies that license IP in the area of nanotech are the National Aeronautics and Space Administration (NASA) Ames, Lawrence Livermore National Laboratory (LLNL), and Lawrence Berkeley National Laboratory (LBNL). NASA Ames funds a quasi-independent organization called the Girvan Institute to help in this process of promoting NASA's IP.

Likewise, universities have offices that focus on the commercialization of their locally generated IP. In California, Stanford and the California Institute of Technology (Caltech) have very good reputations for being easy to work with. Although the universities in the UC system generate a good amount of high quality IP in the area of nanotech, they unfortunately have a reputation for being more difficult to work with. Despite these limitations, it has been our qualitative observation that the majority of IP that is licensed by startups comes from universities and not from government labs, mainly attributed to the differences in their sum total of research output.

The most currently visible nanotech company, Nanosys, was formed in this way. Nanosys' stated strategy is to "build a dominant technology and intellectual property estate through a combination of aggressive technology in-licensing, teaming with the world's leaders in academic nanoscience, internal technology development, discovery and patent filings."[1] Nanosys has licensed IP from the following universities to date: Columbia, Harvard, LBNL, the Massachusetts Institute of Technology (MIT), UC Los Angeles, UC Berkeley, and Hebrew University.

It is very common for the filer of a patent to be involved in the commercialization of the technology. One study shows that 70% of university inventions can't be utilized without the involvement of the inventor. We have seen many examples of this – for example Axon Technology Corporation was formed with IP from Arizona State University and the professor who generated the IP is still involved with the company.

Spin-Outs

Another way that nanotech startup companies are formed is by a parent company spinning-out a business unit. In the recent IPO market environment, these spin-outs have not gone public, but are typically held as subsidiaries. A recent small-tech example of this is the MEMS Computer Assisted Drafting (CAD) company, Coventor, who spun out their radio frequency (RF) MEMS

[1] Nanosys, Inc. website, www.nanosysinc.com/about.html.

unit to create WiSpry. Previously, Coventor had spun-out another business unit into a new company to focus on optical MEMS.

The parent company has a number of advantages in doing this. First, the net value of the two separate companies can potentially be higher, especially if the parent is a large company, although this will not be a major consideration until the markets for IPOs return. Secondly, by spinning out a division, the parent allows for other sources of capital to fund the operation.

Independent Entrepreneur

The final way we see nanotech startups formed is through the independent entrepreneur who generates IP. This case is not the norm and we have not seen any companies likely to make an impact which were started in this manner. We believe the reason for this is that the complexity and expense required to both develop a new nanotechnology and to file the appropriate IP is considerable, and therefore not accessible to most independent entrepreneurs.

The development phase is expensive for a number of reasons. Nanotechnologies are based on physical science. Therefore the capital costs to set up a laboratory to do research and development tend to be high. One commonly used piece of equipment in nanotechnology, an atomic force microscope (AFM), costs on the order of $100,000 for the least expensive model. [2] And there are many more pieces of equipment that are typically required. At the far extreme, many nano companies plan to use semiconductor-like manufacturing facilities, though this is not the bottom-up holy grail promised by nanotechnology. It is widely known that a state of the art semi-fab today costs in the billions of dollars. [3] This is opposed to a dot-com company or a software company where the only capital costs are those of computers and inexpensive software development tools.

> THE CAPITAL COSTS TO SET UP A LABORATORY TO DO RESEARCH AND DEVELOPMENT TEND TO BE HIGH.

One of the key attributes of nanotechnology is the convergence of different areas of science. Because of this, most nanotechnology projects require a multidisciplinary team. Consequently, the labor costs required to develop nano IP also tend to be high.

Success Factors

It should be no surprise at this point that we believe one key success factor is a strong IP position at the inception of the company with a plan to develop that asset over time. Another success factor is a clear, concise, well thought-out and compelling business plan. A good business plan shows that the founders have thought through all the major issues they are likely to encounter in building their business. The critical components of a business plan focus on the issues that will enable the company to bring its products to market. A good business plan also allows for efficient communication of the business idea to potential investors which will become important in the next step – funding. The business plan needs to be comprehensive and cover more than just the technology. Technologist founders are known for not thoroughly thinking through key business issues such as manufacturing and sales channel strategies. [4]

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[2] S. Nett, CEO of Quantum Polymer Technologies Corp, private communication December 9, 2003.

[3] T. Wells and J. Paddon, "Activity-Based Fab Cost-of-Ownership Modelling for Prediction and Optimization of Profitability", Semiconductor Fabtech, Edition 10, February 2000.

[4] Author's own experience.

Another area of the business plan that is linked to success is the executive summary. This section needs to get key points across in a few words and must give a concise and comprehensive picture of what the company will do and how it will make money. Writing this well is also frequently challenging for a technologist founder, which is usually the case in nanotechnology. Luckily there are many resources available to help in writing executive summaries and business plans.

Another success factor is that of a well-balanced team – or at least having a plan to put one in place in the future. There are two aspects to a well-balanced team that we believe are important to a nanotech startup. First, the team needs to have the multi-disciplinary skill-sets needed to accomplish the business plan goals. Sometimes we have seen founding teams where all the members were from the same academic discipline but where the product required a multi-disciplinary team to execute. An example of this was a micro-array company started by two geneticists. Their planned product required a significant amount of MEMS and electrical engineering talent to be designed, but that knowledge was not present in the founding team.

The other aspect of a well-balanced team is having senior people who come from the domains where the product will be sold. For example, when forming a nano-based memory company, it is vital to have a founder who comes from the semiconductor memory space. Without this person, the company is in great danger of developing products that are not appealing to the marketplace. Or worse, the company could be blind-sided by an incumbent technology that challenges the benefits of the new nano-based technology. Finally, having a founding team member with contacts into the space helps facilitate both sourcing relationships and generating first sales. An example of this is an RF MEMS company that we looked at that has executives from both Intel and Analog Devices. The former relationships of these executives are ideal for this company both on the supply side and on the sales side.

Pitfalls

One common pitfall at the inception stage is what Tom Baruch, founder and managing partner of CMEA Ventures in San Francisco, calls "a cure looking for an illness." [5] A classic example of this is the discovery in 1991 of the carbon nanotube by Sumio Iijima of NEC in Japan. It took approximately a decade before significant numbers of researchers began looking for applications of this novel new material class. Even today, there are only a few commercial products that make use of carbon nanotubes.

In many of the nanotechnology companies that we have looked at, the founders could not convincingly articulate a realistic and fundable manufacturing strategy.

We previously discussed the importance of clearly thinking through manufacturing and sales channel strategy early on. Because this is so frequently not done adequately, it is worth re-emphasizing here. For example, in many of the nanotechnology companies that we have looked at, the founders could not convincingly articulate a realistic and fundable manufacturing strategy. One example is a roll-to-roll electronics company planning to develop devices based on new materials using a new manufacturing process. By requiring both the development of a new technology and the development and construction of a new manufacturing methodology, this company was putting itself in a difficult position of requiring a significant amount of capital to take its products to market. Particularly in these times of recession, when investors are focusing sharply on "capital efficiency," this type of strategy is unlikely to gain much interest.

[5] T. Baruch, MIT • Stanford • UC Berkeley Nanotech Forum, Nanotechnology Investment Panel, July 24, 2003.

One buzzword frequently heard these days is that of "platform technologies." This is usually meant in a good way – that a technology will underlie many other new technologies thereby deriving revenue streams from many different application domains and becoming a de-facto standard. The problem with platform technologies is that they can also cause lack of focus in a startup company. Nanotechnology is ripe with platform technologies – a few prominent examples are quantum dots, carbon nanotubes, and nano wires each of which can be used for bio, IT, and other applications. But the danger of not focusing on a particular application can often be deadly for a startup company, so much so that most VCs will force a startup that has multiple divergent products to drop all but one. An example of this is Nanomix – a carbon nanotube focused company that concentrated on applications in both hydrogen storage and in sensors. They have shifted their priorities to de-emphasize the hydrogen storage application in favor of attacking the many market sub-segments that can be served by their carbon nanotube sensor technology. [6]

A final common pitfall that we see in nano startups is failing to plan for the progress that an incumbent technology will make during the time it takes to develop the nano-based technology. This is a classical mistake that many made long before nanotech was a buzzword. The reasons that it is such a common problem in the area of nano is that many nano technologies are focused on disrupting already existing markets and not on creating new markets. An example of this is the multiple initiatives in the nano-based memory space. There are multiple startups as well as large company efforts in this area. In this space, the incumbent technology is semiconductor memory: DRAM, SRAM, and flash memories specifically. It is not sufficient if a nano-based memory technology in prototype stage is competitive with today's semiconductor memories. It must be competitive with the future generation of semiconductor memories that will be mainstream when the nano-based memory becomes a commercial product. A further requirement is that the nano-based technology must be able to at least track the roadmap for semiconductor memories otherwise it will fall behind in a future generation.

3.2.2 Funding Common Strategies

There are many sources of funding. The ones typically considered for a nanotech startup are: friends and family, angels, VCs, government, and corporate partners. We can consider friends, family and angels as a single category. Usually this category can only fund the writing of the business plan and perhaps licensing some IP from a university or other source. As stated before, nanotech companies usually have significant capital requirements to make real progress. But because nanotech is a hot area in the press, it is possible to find high net-worth angels that will put in significant funds. An example of this is MagiQ Technologies. This company's last round of funding of $6.9 million was done entirely by angels which included Jeff Bezos, the founder of Amazon.com. [7]

The government is another source of potential funding. There are many government programs, only a few of the most prominent ones will be discussed here. One program, the SBIR (Small Business Innovation Research) [8] reserves a specific percentage of federal R&D funds for small business. The funds are distributed via many government agencies such as DOE, DOD, and NASA and are awarded in response to solicitations from those agencies. Defense Advanced Research Projects Agency (DARPA) is another common source of funding for new nanotechnologies.

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[6] K. C. Janac, former CEO of Nanomix, private communication, 2003.

[7] T Freeman, "Bezos backs encryption startup", The Deal.com, November 5th, 2002.

[8] U.S. Small Business Administration, Office of Technology SBIR/STTR, www.sba.gov/sbir.

DARPA awards grants in accordance with its interest in developing technologies for military use. A final high profile government project is the National Institute of Standards and Technology's (NIST) Advanced Technology Program (ATP).[9] ATP is unique in that it does not solicit projects in any particular area. Instead, projects are awarded this grant if they can be shown to be of high risk and of high value to the nation; cost sharing is required. An example of this in the nano space is the teaming of General Electric and Molecular NanoSystems which received a $5.8 million ATP award to develop a synthesis platform for growing large arrays of aligned nanorods. For the year 2003, the ATP program is not active. It is anticipated that it will become active again in 2004.

One of the most well known forms of funding is through VCs. There are about ten VCs in Silicon Valley that have funded "nano" deals. The most active and visible of these is Draper Fisher Jurvetson (DFJ) which has invested in roughly eight nanotechnology startups. Looking across the entire U.S., some of the most prominent "nano VCs" are: Venrock, Harris and Harris, NexGen, Apax Partners, Morgan Stanley, and Ardesta. Many other VCs have an interest in nano as the "next big thing" but have not made investments yet. A recent example of a nano company that successfully raised $30 million in its third round from eight investors, both VCs and corporate VCs, is Optiva.

A difficulty with raising money from traditional VCs is that they have very stringent requirements on what constitutes a good investment. Typical negatives are excessive capital costs (e.g. needing to build an expensive manufacturing plant), too small a market for the end product, or too long a time frame to reach revenue. VCs that are part of large corporations (corporate VCs) may not be as stringent on these requirements because they typically make investments that have a strategic value to the corporation. Corporate VCs can be a very good funding avenue for a nano startup also because they can bring some of the non-financial resources of the corporation to benefit the startup. Corporate VCs also have the additional benefit of frequently acting as a respected source of due diligence on a startup company – frequently attracting other traditional VCs that may have had a difficult time evaluating the nano startup's technology. An example of a corporate VC making a nano investment is Eastman Chemical's investment in Konarka.[10] Eastman sees Konarka's technology as a possible consumer for Eastman's advanced polymers – more than just a vehicle for pure financial return.

Besides being investors, large corporations can also be partners in a joint venture, or simply a customer, or some combination of investor, partner and customer. For example, we have seen a number of times when very prominent Silicon Valley based chip-makers have been both investors and customers for a startup company.

Success Factors

There are many success factors in funding. In government funding, writing a good proposal that satisfies the soliciting agency's requirements is one. For VCs, having a strong "done it before team" addressing a large market opportunity is a good start. But these are not unique to nanotechnology. Probably the one thing that seems somewhat unique to nanotechnology is the strategy of having "luminaries" involved with the company. Typically these luminaries are on the founding team or on one of the advisory boards. Frequently these luminaries are high profile academics who have actually generated some of the IP that the company is based on. One example is Nanosys that has a scientific advisory board consisting of the "who's who" in nanotechnology.

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[9] The National Institute for Standards and Technology, Advanced Technology Program, www.atp.nist.gov.

[10] Konarka Technologies, Inc. press release, May 13, 2003, www.konarkatech.com/news_press.php.

Pitfalls

One common pitfall that we have mentioned in section 3.2.1 was that of lack of focus. This is an important issue with investors such as VCs which is why we are bringing it up again here. VCs do not generally like investments where there are multiple disparate target markets. If a VC invests in a company that has such a business plan, it will usually use its influence on the board of the company to focus on just one market. Frequently investors just pass on companies that have unfocused business plans. One example of this that we saw was a nano startup that was having trouble raising capital because it was targeting four markets (memories, logic, displays, and batteries).

Another pitfall is looking for the wrong kind of money (really the wrong kind of investor). An example of this is if a nano company is too far away from a potential product (more than five years) then it should not approach VC investors, it should focus on government sources of funding if applicable.

Nanotechnology is frequently pushing the edge of knowledge, thereby making some investment opportunities very difficult for conventional VCs to assess from a technical point of view. A nano company may have more success going to a corporate VC which has very deep technical resources that can evaluate the technology of the startup. An example of this is a nano company whose technology was based on "new physics." Many traditional VCs shied away from the investment since they were not able to ever convince themselves of the validity of the technology. The company finally got funding from a large technology corporation that has hundreds of researchers capable of verifying the new nanotechnology and understanding its potential application to the big corporate products.

A problem related to the lack of technical understanding is a lack of business understanding by VCs. Since the idea of a nano company is relatively new, there are not a lot of success models for investors to compare to. Worse yet, VC partners typically come from previously successful companies in a particular hot application area. Since nano has not produced those companies yet, there are not a set of VCs who come from nano companies. All this leads to a higher barrier for nanotechnology companies to get funding from conventional VCs.

Although government funding is good because it does not dilute the equity of the company, it can have the negative impact of diverting the company from the planned path of execution. A company that is funded by government grants needs to be careful that they accept only grants that are highly aligned with the direction that they were already heading in. If not, the startup could end up becoming a company that exists for the purpose of getting government grants without ever having a commercial application.

Just as accepting government grants can have a negative consequence, so can accepting corporate VC funding in some circumstances. As we mentioned before, corporate VCs usually have strategic objectives in their investments. This can become a conflict if the corporate investor insists on terms of investment that hinder the nano startup from having relationships with the investor's competitors. We have seen an example of this happen where a nano materials company got an investment from a large electronics company, but the investment came with restrictive terms on who the startup could sell its product to in certain application domains.

3.2.3 Growth

Common Strategies

We have seen a few different strategies that are commonly used by nanotech startup executives to grow their companies. One is to partner with a larger corporation. We discussed this in the context of funding, but it can also be a viable strategy for growth. Partnering can give a company access to manufacturing and to sales channels, both of which are expensive to develop for a startup. An example of this is Thinfilm Electronics and Intel Corp. Thinfilm is working on developing a new type of nonvolatile memory technology. [11] Although we do not know the precise nature of their relationship, except that Intel has made an investment in them, we know from conversations with Thinfilm that they are working very closely with Intel. If Thinfilm's technology is successful, they will presumably have access to a large market via Intel's existing market position.

Another strategy for growth, that we have seen a number of nanotech startups take, is to spin off technologies from a common underlying technology. This approach, as long as it is taken in a serial approach and is not defocusing, can be a good one for a company that has developed a platform technology that can impact many application areas. One example of this strategy in action is General Nanotech. They have developed a pool of IP – 45 patents or applications – centered on atomic force microscopy (AFM). [12] They created a core business, General Nanotechnologies, based on this IP and have spun out one application of this technology. The spinout, RAVE LLC, is focused on using AFM's for making semiconductor mask repairs.

Success Factors

The single most important success factor that we have seen for the growth phase of nano companies is that of having a management team that has strong target market knowledge. For a company to pass the funding stage, it usually need to prove convincingly that it has a nanotechnology that has high market potential. But taking that raw technology to a market is a different skill set than developing the technology in the first place. We mentioned this as a success factor in the funding phase, but it is even more important in the growth phase. We have seen examples in which companies that have created a nano-based technology with a target market in mind discover that the product did not meet the needs of that target market. This oversight was due to lack of domain knowledge on the management team.

Pitfalls

There are a number of pitfalls that we have seen nanotech companies fall into in the growth phase. One is making the transition from academic lab to commercial product. It is common for academic founders to underestimate the difficulty in commercializing a new technology. It is much more difficult to make something in high quantities at a certain level of quality and consistency than to demonstrate something in a lab. A prominent example of this is a nano materials company that we looked at which took five years, versus their planned two years, to bring their new material to market.

It is common for academic founders to underestimate the difficulty in commercializing a new technology.

Another pitfall that we anticipate will be a problem for numerous nanotech based companies, is that of resistance to new approaches by conservative incumbent markets. Many nanotechnology based products are targeted at

[11] Intel Capital portfolio company description, www.intel.com/capital/portfolio/companies/thinfilm.htm.

[12] V. Kley, CEO General Nanotechnologies, private communication, December 10, 2003.

existing markets as previously noted. To be successful, these new products will need to displace the incumbents based on price or performance. But beyond this, the nano based products will need to be proven to have the same quality and reliability as the existing solutions. In conservative industries, such as IT or telecommunications, gaining the track record on reliability could take longer than nanotech company CEO's expect. Virtually every nano based memory company that we have looked at had the expectation that they would ramp the volume significantly within the first year after the introduction of their first commercial product. We have been skeptical of this position.

As we have previously stated, many nanotechnology companies are targeting existing markets with superior nano-based products. Some nanotech solutions can have the effect of potentially unifying fragmented markets. An example of this is using carbon nanotubes (CNTs) as sensors. CNTs can be used as a platform technology for building many types of chemical and other types of sensors and at a potentially greatly reduced cost as compared to existing technologies. The difficulty for the company attacking this opportunity is that the sensor market is really a combination of fragmented markets that are currently served by a variety of vendors. This will make channel development more difficult for the startup.

The final difficulty that we see in nanotech companies in the growth phase is the lack of industry infrastructure. Once again, because these companies are typically on the cutting edge of technology, there is not an existing well-developed infrastructure to leverage. Things that other companies can take for granted – such as an abundant technically trained workforce, manufacturing equipment, manufacturing services, design software – are all minimal or nonexistent for various nanotechnologies. Therefore, nanotech startups are forced to create more of their own infrastructure as they progress.

3.2.4 Exit

Very few nanotech companies have had successful exits to date. This is due to a combination of the state of nanotechnology and the state of the economy. For this reason, it is difficult to talk about "best practices" regarding exits for nanotech companies. Of course there are a limited number of options here: IPO, acquisition, merger, or staying private. We are only aware of one nanotech IPO (of course this depends on how you define nanotech) that is Nanophase. This company has been public for many years and has a relatively small revenue and market cap so it will not act as much of a model for others to follow.

In the current market, an acquisition is much more likely. Coatue, a molecular memory company, was recently purchased by AMD, a large semiconductor memory and microprocessor company. [13] The purchase is strategic for AMD since it gives them a potential position in a technology that will eventually be disruptive to one of their current businesses. This acquisition is believed by some analysts to be the catalyst to force many of the semiconductor memory companies to make similar acquisitions. In turn, this will most likely drive up valuations on the remaining independent molecular memory companies. Similar events may unfold in other applications areas that are impacted by nanotechnology.

3.3 Business Models

We have seen a number of different business models employed in nanotechnology companies. They range from IP licensing, to product, and to service company models. The service model

[13] P. Clarke, "Coatue secretly sold to AMD, folded into FASL," Semiconductor Business News, August 6th, 2003.

is virtually non-fundable and is not considered in this chapter. The IP licensing model is quite common, particularly in areas where there are large incumbent players such as memories, storage, and displays. Figure 3.1 shows the mix of product versus IP licensing models that we have seen broken down by various application areas. These results are based on our surveys of nanotechnology companies that we have looked at in detail over the past two years.

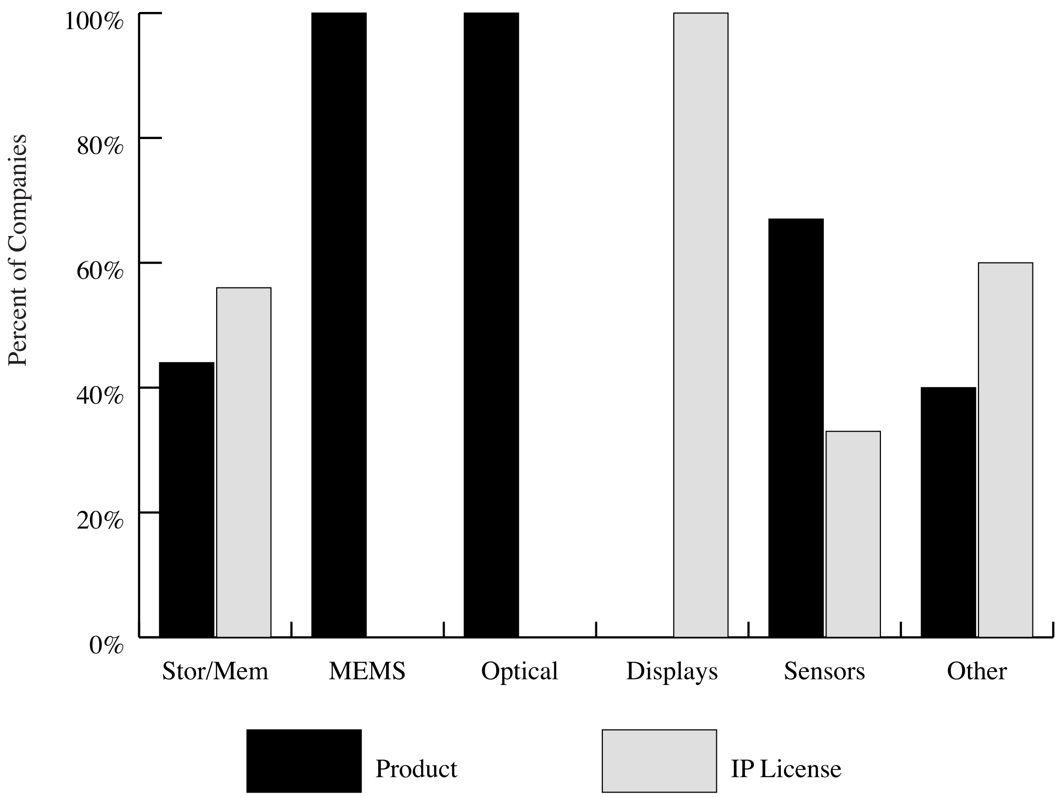

Figure 3.1: Mix of Products vs. IP Licensing Models
Source: Quantum Insight unpublished nanotech startup survey, September 2003

The IP licensing model has an advantage because it allows the nanotech startup company to avoid the expense of setting up manufacturing and sales channels – both expensive propositions. The way the IP licensing model works is that a company develops IP, then licenses it to other companies for commercial applications and finally collects a royalty on the use of the IP. The royalty revenue is then used to fund more IP creation.

The downside to the IP licensing model is that it is difficult to be really successful with it, as seen with examples from other industries such as semiconductors. Rambus is an IP licensing company that had a large amount of success for a period. They licensed IP that was used in the design of high-speed memories for computers. But with their success came motivation for their licensees to find alternatives, which they did, thus, diminishing Rambus' potential going forward. This type of scenario is likely to also happen in the nanotech arena. Therefore, it will be important to ensure very strong IP protection for nanotech companies that are taking this approach. We will talk about IP more in the following section.

Taking the path of being a product company has the drawbacks that were mentioned previously – the potential high costs of setting up manufacturing and sales organizations. The upside is that being a product company is usually a much more defendable position in the value chain. The trick for nanotech companies is to find a strategy that will work well for their particular IP portfolio and the industry that they are targeting.

3.4 Intellectual Property

Intellectual property (IP) has been discussed many times in the preceding sections as being crucial to nanotech companies. Many have drawn an analogy between nanotech and biotech in the importance of IP to both. We consider the acquisition of initial IP to be equivalent to the inception of a nanotech startup.

The value of IP is widely recognized. The number of patents filed at the U.S. Patent Office is increasing rapidly. In 2000, there were 293,000 patents filed while in 2006 it is estimated that there will be 538,000 patents filed – almost doubling in six years. Nanotech patents issued have been increasing at a higher rate. In 1998, there were about 350 nano patents issued while three years later, in 2001, there were over 700 nano patents issued.

This increase in patents being filed and issued is driven by multiple factors. One of those factors is the increased use of aggressive IP tactics such as "patent flooding." In this technique, the aggressor company issues many incremental patents that surround the defending company's IP. This creates a deadlock situation where neither company can use their IP without infringing on the other company's IP. They are therefore forced to cross-license to each other. This essentially gives the aggressor access to the defending company's IP.

With tactics like this being employed, it is becoming very important for companies to have strong IP positions in the technologies that are important to their business. This means not having single patents filed but rather having a layered approach to IP filing. Patents should be filed, if possible, to protect the following levels: composition of matter patents, process patents, and finally application patents. Although we are not lawyers and can't give legal advice, we have seen the above strategy being implemented by savvy firms developing nanotechnologies.

California's Congressional delegation can also address this issue by preventing the diversion of patent fees to other government programs. The Patent and Trademark Office is a self-supporting government agency which is funded by fees paid by patent and trademark applicants. However for the past decade, Congress has diverted $650 million of patent fee revenues to unrelated government agencies rather than allow the patent office to increase its staff to handle the increasing number of patent applications. The healthy development of nanotechnology requires sufficient numbers of well trained patent examiners so that worthy patent applications are rapidly granted while unworthy patent applications are rejected.

3.5 Summary

We have looked at the different phases of the life of a nanotechnology startup. There are challenges unique to nanotechnology that will be faced by the startups. These include the roles played by various sources of risk, technology, management, and market. We have looked at the importance of IP in the field of nanotechnology and the strategies being followed by startups and large companies. We have examined the various business models being pursued by nanotechnology startups.

Like all technology startups, the majority of nanotechnology startups will not be successful. However, the ones that do succeed will have the opportunity to either redefine current industry segments or to create new ones.

Overview of Nanotechnology Commercialization in California

Success Factors

- Well-balanced team with multi-disciplinary skill sets, experience in appropriate industries, and luminaries (to attract funding)
- Addressing a market opportunity of sufficient size
- Knowledge of target market in addition to knowledge of new technology
- Strong IP position
- Clearly written business plan & ability to communicate it

Common Pitfalls

- Creating products based on a new technology, not on market needs
- Diverse research which fails to focus on one product or market sufficiently
- Underestimating the difficulty of commercializing new technology
- Investors who do not understand the technology
- Failure to convert the technology into a viable product
- Accepting funding with restrictions

CHAPTER 4: CALIFORNIA'S UNIQUE POSITION AS A NANOTECHNOLOGY LEADER

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Key Points in this Chapter:

In the next 5 to 10 years...

California's high tech industry base will give state a head start

- Established research & infrastructure leadership in biotechnology, semiconductor, and software technology will kick-start nanotechnology industries in Los Angeles, the San Francisco Bay Area, and San Diego
- The U.S. West Coast will become recognized as the global leader in medical, material and manufacturing nano applications – but Japan will lead in electronic applications and Germany in chemical applications
- The state budget crisis cut funding for UC and workforce training, reducing California's advantage

In the next 10 to 20 years...

California could lose its leadership position

- Europe, Japan, and other U.S. states could close the competitive gap in basic nanotechnology research and economic infrastructures
- Nanotechnology will become a global industry and market – other regions will compete hard, and will attempt to draw away successful California start-ups and manufacturers

4.1 Introduction: Why Nanotechnology?

California is going through a difficult financial period, with some areas like the Silicon Valley being particularly impacted by the economic downturn. The future prosperity of California is being questioned and people are looking for the next engine of growth that will propel the state into another period of success. In this context, nanotechnology, like other technological innovations in the past, is one of the most promising new developments that not only leverages California's unique strengths but also could define the future of California and its place in the global economy.

Nanotechnology is not yet an industry like the semiconductor, software or bio-medical industries. It is still a collection of enabling technologies that impact multiple industries. The semiconductor industry was created after the invention of the integrated circuit, as different players created and found their niches in the semiconductor value chain. There is no equivalent of the "integrated circuit" in the world of nanotechnology; therefore the primary role of nanotechnology currently is to support, augment and enable the existing industries. The potential impact of nanotechnology on existing industries is vast and could fundamentally change the paradigms and economics of some existing industries over the coming decades.

The bigger impact of nanotechnology will lie in the process where future developments may create new industries around fundamentally new capabilities and markets. This is the ultimate prize California needs to be mindful of. The creation of new industries will determine the future prosperity and leadership of California.

4.2 The Global Challenge

California is part of the new reality of globalization where it faces stiff competition from other areas across the world in innovation, manufacturing and distribution. It is clear that through globalization, the role being played by California in existing industries will change, as more and more companies feel compelled to move some of their business functions elsewhere. Multi-national companies are making decisions about where to locate different business functions based on factors such as cost, business risk, proximity to talent, and market access. These factors vary by region across the global economy, endowing regions with different competitive advantages for different business functions. As a result, today business functions are seldom co-located in any one region and global firms compete effectively by connecting the best of what each region has to offer, locating business functions where they provide the best combination of cost, quality, and other advantages.

> The comparative advantages of California will continue to shift as other regions make strategic investments in education, R&D, and other infrastructure.

In such times of transition, it is essential to identify the sources of strength and competitive advantage for the state, and to chart a course for the future that builds on existing strengths. The comparative advantages of California will continue to shift as other regions make strategic investments in education, R&D, and other infrastructure. As a result, California must constantly renew its advantage and unique strengths, or risk the consequences.

California's major industries must keep renewing themselves through innovation and entrepreneurship and finding new ways to add value to preserve and improve the standard of living. In addition, like in the past, California should look to the next waves of innovation that could create new industries altogether. If California resists change and fails to renew its current centers of industry and innovation, like the Silicon Valley, Los Angeles and San Diego, it might slip into a prolonged economic decline as seen in other regions like Pittsburgh or Detroit that once dominated the driving industries of steel and automobiles respectively. Therefore, California must pursue new sources of prosperity that define its leadership position within the new global competitive pressures.

4.3 California's Unique Strengths

Successful innovation and commercialization of nanotechnology, like any new technology, is not easy, as there are significant technological, business and talent risks involved in the process. Therefore, it is unrealistic to expect that nanotechnology companies would automatically migrate to a given area. Fortunately, California is uniquely positioned to be a leading center of innovation and commercialization for nanotechnology.

California is unique in the country, if not in the world, in terms of its successful track record and the variety and depth of assets it possesses for technology innovation and commercialization. California has seen the semiconductor, computer, software and bio-medical industries blossom. Innovations in these industries have revolutionized the lives of people around the globe and established California as the pre-eminent high-technology leader around the world. The key innovations in all of these industries have not necessarily come from California, but California has played a decisive role in the successful commercialization of innovations that have led to these industries.

These successes have derived from, and indeed contributed to, unique regional assets that remain critical to economic success, like its entrepreneurial culture, capital and people. It also has specific assets that are particularly important for nanotechnology innovation, such as companies and research institutions working on bio-, info- and nano-technology and their applications to various industries.

At a high level, the following prominent assets drive the unique position of California as a future nanotechnology leader:

1. The environment, tradition and talent for entrepreneurship and innovation;
2. An established leadership position in the semiconductor, computer, software and biotech industries; and
3. Pre-eminent research institutions and universities.

We believe that these assets work together and have, in this order of priority, defined the innovation and commercialization leadership position of California

4.3.1 Strength #1: The Environment, Tradition and Talent for Entrepreneurship and Innovation

California contains two of the pre-eminent centers for entrepreneurship and innovation in the country. The Silicon Valley, based in Northern California, is a center for the semiconductor, computer, software and biotech industries. The San Diego Area is a center for the biotech industry. The Los Angeles Area is another promising region, potentially in the area of nanotechnology.

All of these areas consist of dense, flexible networks and relationships among entrepreneurs, venture capitalists, university researchers, lawyers, consultants, highly skilled employees and others who know how to translate ideas into new commercial products and services fast enough to stay on the edge of the innovation curve. These complex networks continually connect people to good ideas and test the changing market, always searching for the next innovation.

Silicon Valley provides a great example to illustrate this further. A similar analysis would apply to both the San Diego and Los Angeles Areas.

Silicon Valley has become known as much for its innovation and entrepreneurship as for any specific industry or technology. The region excels at applying and commercializing new inventions. Waves of innovation typically begin with scientists – including those in other regions – producing technological breakthroughs. Entrepreneurs then innovate and bring new ideas to market, thereby amplifying the wave. In this respect, Silicon Valley's culture of tolerance for entrepreneurial trial-and-error is critical to the risk-taking required for innovation.

The authors of The Silicon Valley Edge [1] first used the term "habitat" to describe a favorable environment for innovation. They observed that:

> "Like a natural habitat for flora and fauna, the habitat of Silicon Valley is one in which all the resources high-tech entrepreneurial firms need to survive and thrive have grown organically over time. Silicon Valley's habitat includes people, firms, and institutions – their networks and modes of interaction. And, like a natural habitat, it is marked by complex, dynamic, interdependent relationships."

More specifically, they list ten features crucial to Silicon Valley's habitat: [2]

- Favorable rules of the game – A system more favorable to new business ventures than the systems of other countries

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[1] Lee, Chong-Moon, William F. Miller, Marguerite Gong Hancock, and Henry S. Rowen, editors, The Silicon Valley Edge: A Habitat for Innovation and Entrepreneurship, Stanford Business Books, 2000, p. 3.

[2] Ibid., pp. 6-13.

- Knowledge intensity – Silicon Valley is a melting pot of ideas for new products, services, markets, and business models
- Open business environment – Individuals and companies are open to new partnerships and mutually beneficial exchanges of knowledge
- Results-oriented meritocracy – Success is propelled by imagination, ability and achievement, leading to large numbers of immigrants to the region to succeed
- A specialized business infrastructure – An established foundation of support services for new businesses – These include venture capitalists and bankers, lawyers, headhunters, accountants, consultants, and others
- A high-quality and mobile workforce – The Valley attracts exceptional talent, including entrepreneurs, whose ranks are continuously replenished, bringing in new perspectives, stimulating innovations, and launching new firms
- Universities and research institutes that interact with industry–Ideas and knowledge pass in two directions in a variety of ways
- Collaborations among business, government, and nonprofit organizations–Working relationships among companies, governments, associations, and others provide the means to address key issues and community needs
- High quality of life – The natural, cultural, historical, and intellectual qualities of the region have been major attractions for talent and companies

It is important to remember that what has set Silicon Valley apart "are not the technologies discovered here, but the companies created in the region that develop, market, and exploit these technologies. In other words, the Silicon Valley story is predominantly one of the development of technology and its market applications by firms–especially start-ups." [3]

The Silicon Valley environment for innovation and entrepreneurship has enabled the region to make repeated leaps with new technology waves over the last four decades, from leadership in integrated circuits in the 1960s to personal computers in the 1980s to the Internet in the 1990s. All of these innovative leaps occurred in the face of rising costs, growing competition and increasingly rapid diffusion of technology.

4.3.2 Strength #2: An Established Leadership Position in the Semiconductor, Software and Bio-medical Industries

Nanotechnology is fundamentally multi-disciplinary. It requires the participation of people and institutions from different backgrounds that have not traditionally closely collaborated. This multi-disciplinary nature is illustrated by some possible applications of nanotechnology: computer memory based on switching of organic molecules, fuel cells with enzyme activated membranes and ultra-sensitive chemical and biological detectors based on silicon cantilevers. In addition, the development of these applications would require fast and accurate computer simulation and modeling at the atomic scale.

Fortunately, California enjoys a leadership position in the disciplines that will impact nanotechnology directly – semiconductors, software and bio-medical. California is home to many household names in these industries.

Almost every major company in these industries has a critical business function centered in California: headquarters, research & development, production, or sales/marketing and distribution. Most of these companies are concentrated in regions like Silicon Valley and San Diego, as mentioned previously.

[3] Ibid., p. 3.

Silicon Valley, again, provides a good illustration of this. Silicon Valley is already an established leader compared to other regions in key areas of innovation. There is a great deal of activity in Silicon Valley involving partnerships with other companies for breakthroughs in multi-disciplinary applications. Here are some illustrations of such multi-disciplinary work involving companies based in Silicon Valley.

Computer companies with large research labs such as IBM and Hewlett-Packard have developed substantial nanotechnology programs. IBM researchers have already successfully demonstrated carbon nanotube transistors that substantially outperform advanced silicon devices.

Hewlett-Packard researchers have patented a potential breakthrough in memory, where bits are stored in individual molecules. Intel announced a new chip-design breakthrough that will enable the development of cheaper and faster microprocessors based on nano-level technology with more than one billion transistors compared to 42 million in Intel's latest Pentium 4 chip.

The continued miniaturization of integrated circuits requires working at the molecular level. Palo Alto-based Genencor has collaborated with Dow Chemical to build biochips, including biological optical switches using a new technique: silicon biotechnology. Affymetrix bought an old National Semiconductor manufacturing facility in Santa Clara to create biochips that place hybrid bits of DNA on computer chips instead of transistors.

ChevronTexaco has announced the discovery of diamond molecules in oil. This constitutes a discovery of a fundamentally new material potentially at par with fullerenes and carbon nanotubes. The potential uses of these materials include pharmaceuticals, new materials and electronics.

In 2001, the global venture capital firm 3i conducted a survey on nanotechnology. In the survey, they interviewed people from the industry, academia and professional organizations about various aspects of nanotechnology. In particular, they looked at geographical considerations. The survey respondents were asked to identify the countries in which the most sophisticated nanotechnology developments in particular industries are happening.

Not surprisingly, the United States came out on top for every industry, but by splitting the U.S. into regions, a more complex picture emerges (See Table 4.1).

	Medical/Pharma	**Materials**	**Chemicals**	**Electronics**	**Manufacturing**
Rank 1	USA (west) (28)	USA (west) (28)	Germany (25)	Japan (34)	USA (west) (26)
Rank 2	USA (east) (26)	USA (east) (27)	USA (west) (19)	USA (west) (33)	USA (east) (26)
Rank 3	UK (23)	Japan (25)	USA (east) (16)	USA (east) (20)	Japan (21)
Rank 4	Germany (19)	Germany (21)	UK (11)	Korea (17)	Germany (15)
Rank 5	Switzerland (9)	UK (15)	Japan (10)	Taiwan/Germany (9)	Korea/Taiwan (7)

Table 4.1: Ranking of Active regions for Different Application Areas of Nanotechnology (**The numbers in parentheses are the number of respondents for an entry.**)
Source: Nanotechnology: Size Matters. [4]

[4] 3i, Economist Intelligence Unit, and Institute of Nanotechnology, July 10, 2002, at http://www.3i.com/pdfdir/3i_nanotech_techpaper.pdf.

Survey respondents actually considered Japan to be the global leader in electronic applications of nanoscience, Germany to be the pacesetter in chemical applications and the U.S. west coast to lead in medical, material and manufacturing applications of nanoscience.

It is worth noting that the U.S. West Coast stands out from all other regions in the country as the area best positioned to drive innovation in nanotechnology.

4.3.3 Strength #3: Pre-eminent Research Institutions and Universities

The Bay Area, Los Angeles and San Diego are home to some of the most respected universities and research labs in the country. Small Times magazine has identified the Bay Area in particular as having the highest concentration of research and industry capabilities in the nanotechnology field. These institutions include UC Berkeley, Stanford, Caltech, UC Santa Barbara, the University of Southern California, UC Los Angeles, UC Davis, UC Santa Cruz, NASA Ames, Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory.

New interdisciplinary research facilities are being established across the state to augment this existing research capacity. Some specific examples are as follows:

The Caltech Materials and Process Simulation Center is working on predicting the properties of stable nano-structures that might be formed to serve as elements of nanomaterials (gears, tethers) and also on synthetic strategies for creating such structures. In addition, work is being done on predicting structures for surface absorbed monolayers, structures of starburst dendrimer polymers, simulations of liquid crystals, and prediction of images for scanning tunneling microscopy (STM).

> It is worth noting that the U.S. West Coast stands out from all other regions in the country as the area best positioned to drive innovation in nanotechnology.

University of Southern California - Laboratory for Molecular Robotics conducts research on nano-manipulation with scanning probe microscopes and its applications in nanoelectromechanical systems (NEMS).

California NanoSystems Institute UC Los Angeles and UC Santa Barbara have joined to build the California NanoSystems Institute (CNSI) funded by the state, which will facilitate a multidisciplinary approach to develop the information, biomedical, and manufacturing technologies that will dominate science and the economy in the 21st Century. The vision of the CNSI is to establish a coherent and distinctive organization that serves California and national purposes and that is embedded on the UC Los Angeles and UC Santa Barbara campuses. The CNSI will be a world-class intellectual and physical environment that supports collaboration among California's university, industry and national laboratory scientists.

Stanford University - Stanford Nanofabrication Facility (SNF) serves academic, industrial, and governmental researchers across the U.S. in areas ranging from optics, MEMS, biology, and chemistry, as well as traditional electronics device fabrication and process characterization. The National Science Foundation through the National Nanofabrication Users' Network supports the SNF.

Stanford Bio-X Center connects the schools of Medicine, Sciences and Engineering around the use of computational tools in molecular, cellular, tissue and organ research. The catalyst for this work is the new Clark Center, a building designed by Norman Foster that will serve as the hub for 275 interdisciplinary researchers.

Institute for Quantitative Biomedical Research, one of the California Institutes for Science and Innovation will draw on the strengths of three UC campuses (San Francisco, Berkeley and Santa Cruz) in biology, computer science, physics, chemistry and engineering. The goal is to integrate the understanding of biological systems at all levels of complexity, from atoms and DNA to cells, tissues, organs and entire organisms. This will require advances in bioinformatics and bionanotechnology, and could lead to advances such as personalized medicine.

Center for Information Technology Research in the Interest of Society (CITRIS), the other California Institute in Northern California, is a partnership between UC Berkeley, UC Santa Cruz and UC Davis. Leading Silicon Valley companies (e.g. HP, Sun, Intel, Agilent) and private donors have pledged over $170 million to match the state's $100 million investment. The goal of CITRIS is to develop "societal-scale information systems" that can enhance our quality of life by boosting energy efficiency, reducing traffic congestion and improving our ability to respond to natural and man-made disasters.

The Lawrence Berkeley National Laboratory (LBNL) and UC Berkeley both have created new nanotechnology initiatives. LBNL has received approval from the Department of Energy for the $85 million "Molecular Foundry," a national user facility that will provide researchers and Bay Area companies with the cutting-edge tools they need to explore the frontiers of nanotechnology. In addition, UC Berkeley is launching a major initiative in nanoscience and nanoengineering to develop a new multidisciplinary curriculum, recruit additional faculty and create shared facilities for nanoscale imaging and fabrication.

NASA Ames Research Center is planning to expand significantly on its foundation of nanotechnology research activities, including carbon nanotubes (important to nanoelectronic devices, computers and sensors), inorganic nanowires, computational nanotechnology (key to modeling and simulation) and biosensors (including collaboration with the National Cancer Institute to develop a nanoelectronic-based biopsy sampler).

The Focus Center Research Program (FCRP) is a partnership between industry and the Defense Department to support university research in semiconductors. There are currently five focus centers including the Gigascale Silicon Research Center (GSRC) led by the University of California at Berkeley and the Functional Engineered Nano Architectonics (FENA) Focus Center led by the University of California at Los Angeles. California Institute of Technology, Stanford, University of Southern California, and the University of California at Riverside, San Diego, Santa Cruz, and Santa Barbara also participate in this $26 million effort. The GSRC focus center researches the software required to design chips containing billions of circuits and to test the gigascales microchips to insure that the circuits work as designed. The FENA Focus Center was established in 2003 to emphasize post-CMOS technologies enabled by nanotechnology, spintronics, molecular electronics and quantum entanglement. The other three focus centers address interconnect; nanoscale materials, structures and devices; and circuits, systems and software.

> THE PRIMARY EFFECTS OF NANOTECHNOLOGY WILL BE TO ENHANCE THE CURRENT MAJOR INDUSTRIES AND TO ENABLE THE CREATION OF ENTIRELY NEW INDUSTRIES THAT HAVE NOT EXISTED BEFORE.

The IBM Almaden Research Center in San Jose, California has been a leading nanoscience and nanotechnology research facility for years and is currently pursuing research on low-temperature scanning tunneling microscopy (STM) and a magnetic resonance force microscope, as well as numerous nano-fabrication projects. IBM Almaden changed the way people think about nano-engineering when one of its scientists wrote "IBM" using individual xenon atoms in 1989 and remains one of the world's leading nanotechnology research centers today.

The accomplishments and outlook for many nanoscience research and development activities in the Bay Area are highlighted in the forthcoming report from the Bay Area Science Innovation Consortium (BASIC): *Nanotechnology in the San Francisco Bay Area: Dawn of a New Age.*[5]

It is clear that California is well positioned for the coming convergence, given its unique research assets and the associated highly trained and specialized workforce. The challenge for California is to leverage these substantial assets to take advantage of the coming wave of innovation in nanotechnology.

4.4 Impact of Nanotechnology on California

The impact of nanotechnology on California will be deep and long-term. To understand the various drivers of this impact, we should look at the major industries that drive the economy of California today.

In the semiconductor, computer, software and bio-medical industries, inter-related companies are geographically concentrated in specific regions like Silicon Valley and San Diego. These companies sell their products and services inside as well as outside their regions, state and the country and are the major source of exports and wealth creation for the local economy. They create jobs for residents and drive growth of employment in business support industries such as finance, insurance, and real estate, and in population-serving industries such as retail and food services. They also generate revenues for public services through taxation that support the quality of life of the region. In addition, these regionally concentrated companies can be a catalyst for innovation as firms compete and collaborate with each other, and a source of entrepreneurship as talented people move between companies or start their own new companies.

The primary effects of nanotechnology will be to enhance the current major industries and to enable the creation of entirely new industries that have not existed before. There are precedents to both of these scenarios in California's past, as previous waves of innovation have been successfully commercialized.

As in the past, the specific benefits will be in higher employment, revenues for local communities and the state and the creation of a favorable environment for successive waves of innovation.

4.4.1 Employment

The residents of California, especially those living in centers of industry and innovation, will benefit from new occupations and careers, higher living standards, less displacement, and more opportunities to become homeowners, especially among the younger generation.

New kinds of skilled workers will be required. While some new Ph.D.s will be needed, much of the future workforce will likely require bachelor's degrees, associate degrees, professional certificates and other specialized training beyond high school. While there will be few opportunities for low-

5 The report is scheduled for release on 1/30/04; copies should be available at that time from Sally DiDomenico of BASIC.

skilled workers, there will likely be opportunities accessible to a wide range of people, including youth now in elementary and high school, and adults who could make the transition from other occupations if given the appropriate post-secondary education and training.

If California is able to create the education and training programs to meet this coming demand, and current residents are able to prepare themselves, then the next wave of innovation could give the next generation–today's children–an opportunity both to sustain and improve their standards of living. (See chapter 5.)

4.4.2 Revenues for Local Communities and the State

The internet boom of the 1990s saw a dramatic increase in the tax receipts for California, producing record budget surpluses.

Nanotechnology can stimulate the local economies of the various regions of California and enable the creation of new businesses and employment. Local cities and counties and the state will benefit from new public revenues, which will flow back as investment into the state as higher-quality community services and amenities and translate into a higher quality of life for the residents. In addition, new businesses can come into existing communities on mutually beneficial terms so that the residents can enjoy the benefits of economic vitality directly.

4.4.3 Favorable Environment for Successive Waves of Innovation

In the past, each successive wave of technological innovation and commercialization in California has produced an investment in the people and the infrastructure of the state that has fueled future innovation. Just as the success in semiconductor, computer, software and bio-medical industries has become essential to the potential for current waves of innovation, nanotechnology will enable many more waves of innovation through a combination of talent, infrastructure and business environment.

Financial success stemming from nanotechnology will have long-term effects on the quality of life in California. Good quality of life will attract and retain talent and prepare the future generations of innovators.

If the regions of industry and innovation in California are able to anticipate and direct new businesses into existing facilities or into desirable infill downtown locations, then the wave of nanotechnology innovation can be fit into existing communities with a minimum of disruption and sprawl. Similarly, if good and affordable housing is accessible to the younger generation and located so as to minimize traffic congestion, the talented, entrepreneurial workforce can be retained with a minimum of community disruption and sprawl. All of this will have a critical impact on the quality of life, and consequently the environment for future innovation.

4.5 State of Commercial Nanotechnology

Quantum Insight has closely worked with Fortune 500 companies, venture funds and startup companies active in the area of nanotechnology. The managing partners of Quantum Insight have participated in sessions with senior executives and venture capitalists at Fortune 500 companies and large venture funds about the potential impact of nanotechnology. We also run the MIT-Stanford-UC Berkeley Nanotechnology Forum, which highlights the commercial applications of nanotechnology to different industries. Through our activities, we have made the following high-level observations on the state of commercial interest in nanotechnology.

Nanotechnology is the Next Big Thing.

- Nearly all the leading companies in the semiconductor and materials industries have nanotechnology initiatives or are in the process of evaluating new initiatives. These initiatives range everywhere from strategic research and product development to assessment studies of when and how nanotechnology will impact their business. Competitive pressures and declining margins are pushing businesses to look for new areas of innovation and excellence.
- Most agree that successful startup companies and initiatives within large companies will primarily drive the commercialization of nanotechnology.
- Most businesses and investors react positively to the government support for nanotechnology. Many view the NNI and the funding of nanotechnology research as a positive incentive for them to look at nanotechnology.

International Interest is High.

- There is a significant interest in corporate nanotechnology funding and support in Asia and Europe. Many countries, especially Japan, China, Korea and Singapore, look to the U.S. as a model for nanotechnology innovation and research. They are spending significant effort to create nanotechnology programs that align with their existing strengths. For example, Samsung (Korea) is looking at the application of carbon nanotubes in next generation Field Emission Displays. NEC (Japan) has developed Direct Methanol Fuel Cells based on carbon nanohorn technology.

Widespread Commercialization is Years Off.

- Many see nanotechnology as a long-term, high-risk but potentially critical investment. The large companies invest strategically in this area, either in internal initiatives or in start-up companies. Few venture funds have invested significantly in nanotechnology. Those who have invested have participated in syndicated deals with other venture and/or corporate funds.
- Many large businesses (correctly) view nanotechnology as a continuation of the various existing trends in their industries. In the semiconductor industry, it follows the reduction in feature sizes according to Moore's law. In the materials arena, it is a continuation of the trend to understand, manipulate or exploit matter at smaller scales.
- Most expect the short-term (less than three years) impact of nanotechnology to be in areas of materials and their simple applications and certain sensors. Few see large-scale impact of novel capabilities enabled by nanotechnology in the short term. These novel capabilities include quantum devices, most bio-medical applications and new lithography techniques. The semiconductor industry for example, though already in the sub 100 nm realm, sees advanced photolithography still as the technology of choice for the next five years.

Successful Nanotechnology Commercialization Faces Challenges.

- Many industry and academic people agree that there needs to be a streamlining of the technology licensing process from the UC system in particular. The licensing arrangements sometimes take a long time or come with terms that are not palatable to the industry. There are also particular complaints in the case where a university researcher is an innovator and wants to start a new company.
- Many agree that most nanotechnology organizations tend to hype nanotechnology to their own detriment. Many people, especially in the Bay Area, lack the credibility and quality of the MIT-Stanford-UC Berkeley Nanotechnology Forum, which has strong ties to both industry and academia.
- Nanotechnology startup companies face difficult challenges in getting funding, office space, laboratory space and equipment and a trained workforce. These challenges are always

present, but have been exacerbated by the recent economic downturn as well as by the highly specialized needs of the nanotechnology startups. Laboratory space and equipment are of particular importance as they are too expensive for most startups. If shared resources are available to startups and industry alike, with a model akin to semiconductor foundries, then the process of innovation and commercialization can be accelerated. Similarly, office space can be made available in concert with the local city and county governments. This involves creation of regional incubators or research parks.

- Most agree that nanotechnology commercialization will be driven by new startups; however, most of the startups are too technology driven and not business driven to be successful.

There is a Need for a Single Voice in Nanotechnology.

- Most agree that California does not speak with a “single voice” about nanotechnology.

4.6 Goals to Ensure California’s Leadership in Nanotechnology

Despite California’s unique strengths in technology innovation and commercialization driven by startup companies, there is no concerted state-wide effort to support and promote them. It is essential to articulate a state-wide vision to support nanotechnology and to provide an infrastructure that would enable the creation of new startups.

Entrepreneurship, market forces and the alignment of government policies with them have primarily driven the success of California. The key motivation in any policy recommendation would be to support and augment the natural entrepreneurial tendency in California to innovate and not to stifle it with too much bureaucracy. Following are some central goals California should address in protecting its leadership position and laying a strong groundwork for the future.

Consider a State Equivalent of the National Nanotechnology Initiative.

A roadmap for long-term support and promotion of nanotechnology in the state would assist in defining a strategic vision for California and help provide consistent approaches to encouraging nanotechnology research, development, and commercialization. The first step in the establishment of such an initiative would be in the creation of a council staffed by members of the government, academia, and industry, and would enable California to effectively approach the following goals.

Build upon California’s Existing High-Tech Strengths.

California has many of the nation’s leading research universities as well as strong high-tech industry clusters. These are the ideal building blocks for developing California’s nanotechnology leadership, but consistent vision must guide the process and effectively leverage existing resources.

- Establish multiple centers of excellence in nanotechnology and multi-disciplinary R&D at existing universities and laboratories: these centers of excellence would be located in the various hot-spots of nanotechnology research, San Francisco Bay Area, Los Angeles and San Diego. The purpose of the centers of excellence would be to bring various research initiatives together effectively as well as to act as regional centers of innovation.
- Develop collaborative platforms between the research community and industry to enable them to work together as well as for the commercialization of developed technologies: industry and academia needs to work together for both innovation and commercialization of nanotechnology. The creation of flexible arrangements whereby industry can support research at universities would be beneficial to both. Importantly, the process of commercialization would be accelerated with better mechanisms for the licensing of technologies from the UC

system in particular. There needs to be a policy that encourages industry participation by giving them more comprehensive intellectual property rights to enable them to successfully commercialize new innovations.

- Create and support shared laboratory space with specialized equipment that can be used by academia, industry and startups: these for-rent lab spaces can be located at the centers of excellence and can provide an efficient means of providing equipment and technical expertise to the industry to enable accelerated innovation and commercialization.
- Create and support of public platforms like the MIT - Stanford - UC Berkeley Nanotechnology Forum for effective communication of nanotechnology developments and for the facilitation of new startup creation: effective, credible and constant public communication of the innovations, opportunities and applications of nanotechnology will maintain the momentum for California's nanotechnology strategy. Such platforms enable the creation of new startup activity by bringing together people from the research, entrepreneurial and industrial communities.
- Develop incentives and resources for nanotechnology startups, including funding and incubator spaces. To enable entrepreneurial activity, limited resources and incentives should be made available to startups on a purely competitive and merit-driven basis. For example, seed funding would enable viable startups to survive until they are able to secure institutional funding and/or customers. Similarly, incubation spaces would provide startups with a home to develop their teams and their technology.

Build the Environment for Innovation.

California will require support and the infrastructure to enable it to compete and retain its leadership in the future. Innovation is fundamentally about people, and California needs to continue to invest in building the best environment for innovation. There are multiple aspects to building an environment supportive of innovation:

- Invest in education to create the innovators and workforce of tomorrow: curricula at all levels should include the multi-disciplinary education needed to create the innovations of tomorrow. In addition, new career planning services and recruitment initiatives are required to plan and position for the new careers and occupations of the future.
- Improve the quality of life issues in order to attract and retain talent in California: faced with growing competition from other areas, California has to address the long-standing quality of life issues including affordable housing, public transportation and K-12 education.
- Build mechanisms that promote closer collaboration between the industry, startups and the local city and county governments: the community at large should recognize the importance of innovation and entrepreneurship and work hand-in-hand with new businesses for their establishment. This would create greater efficiency in the usage of existing office space, keep urban areas vibrant, and create a mutually beneficial win-win mindset between all members of the community.

4.7 Conclusion

Nanotechnology will be a lasting wave of innovation that will fundamentally change the way we live and positively impact our lives. California possesses exceptionally unique strengths that favor its leadership position in this wave of innovation. In order to utilize these strengths, we need a state-wide initiative to unify the various nanotechnology participants and to provide a long-term vision. An equivalent of the National Nanotechnology Initiative for California is proposed.

The reality of globalization and the recent economic downturn have highlighted the need for new avenues of innovation and wealth creation that will maintain and enhance the prosperity of the state. California stands at a cross-roads. The state can be complacent and rest on its laurels or make an active investment in inventing and securing its future.

CHAPTER 5: PREPARING CALIFORNIA'S WORKFORCE FOR THE NANOTECHNOLOGY INDUSTRIAL REVOLUTION

Gus A. Koehler
Time Structures

Key Points in this Chapter:

In the next 5 to 10 years...

California's education and training systems face challenges

- California will suffer a severe shortage of qualified nanotech workers, due to demographic shifts and lack of K-12 preparation, especially among minorities
- California's disadvantages in global manufacturing productivity will lead to continuing job loss
- California will attempt to catch up with Massachusetts, Maryland, New Mexico, and several nations who have a head start in strategic initiatives for nanotech research and workforce training

In the next 10 to 20 years...

Workforce training will adapt to the needs of the nanotechnology industry, provided that suitable initiatives are adopted in California

- Colleges and universities will develop interdisciplinary training and R&D capacity
- California will regain a competitive position relative to other states and nations, in training and research education capacity
- Trained immigrants will sustain California's researcher and workforce industry cluster advantage

5.1 What are the implications of Nanotechnology for California's Research and Manufacturing Activities?

A number of California's key industries – materials manufacturing, energy, biotechnology, medical instruments, computers – are on the verge of what Darby and Zucker, in chapter 2, call a dramatic, metamorphic revolution, one that will change everything from what products are produced to how they are manufactured. This revolution is driven by nanotechnology. Today California is out in front in some aspects of nanotechnology but this revolution is so new, so different, that the complete dominance of any one region is not assured. Darby and Zucker also point out that:

> "California has a powerful lead in the science and engineering base for nanotechnology, and this provides hope that a disproportionate share of the metamorphic progress due to the nanotech revolution will be concentrated in California. However, the lead is smaller for the very fields with the most immediate application to industry, suggesting that California cannot afford to sit on its scientific laurels and expect to be the big winner in nanotechnology."

Manufacturing is an important sector of California's economy. The National Association of Manufacturers (NAM) recognizes the importance of nanotechnology to manufacturing's future.

"After 31 months of consecutive net job losses now amounting to two million, it has never been clearer that the United States must push even harder to lead the rest of the world in technological sophistication and productivity. The race for the world lead in nanotechnology is one that the United States simply cannot afford to lose. Without question, the race begins in the laboratory. At the same time, the NAM will be promoting the earliest feasible manufacturing applications of research results." [1]

This race is taking place in a world where manufacturing dominance is already driven by relentless advances in technology, cost of labor competition, and demographic shifts in the age of skilled workers leading to increased dependence on younger workers, and the rapid movement of capital.

This chapter of the report briefly addresses the following questions:

- What is required to support the development of nanotechnology?
- What products is nanotechnology likely to produce and what skills is the workforce likely to need over what time period?
- Are nanotechnology curricula being developed for higher education and technicians?
- How well prepared is California's workforce to address nanotechnology's scientific and technical challenges?
- Where are California's nanotechnology regional industry clusters located?
- Who are California's global and state competitors and where are they in the race to generate a competitive advantage to dominate the new industry?
- What critical time limited actions are necessary to keep California's nanotechnology competitive advantage?
- What can California's research, workforce training, and related state programs do to support the rapid emergence of nanotechnology industry clusters?

The central policy making thread that ties each of these sections together is timing: can the right government elements be put in place such that basic research discoveries and resulting commercialized processes and products are continuously produced in a supportive environment leading to competitive advantage in multiple nanotechnology influenced industries?

5.2 What is required to support the development of nanotechnology?

5.2.1 Dynamic Competitive Advantage

Basic science discoveries and their commercialization are key to making the breakthroughs that are driving nanotechnology today, but these developments are not sufficient to lead to economic dominance. It is the active tie between the basic science discoveries and leading edge manufacturing that results in technology leadership. Darby and Zucker [2] argue that inventions of new procedures or instruments such as the atomic force microscope are what is setting off this new industrial transformation. These new instruments provide access to whole new ways of inventing and in parallel, whole new ways of manufacturing. On the one hand, the scientific infrastructure is needed to produce such discoveries; on the other hand the technological infrastructure is needed to take commercial advantage of them.

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1 National Association of Manufacturers, Manufacturing Institute, and Deloitte and Touche (2003). Keeping America Competitive. Washington D.C.

2 Darby, Michael R., and Lynne G. Zucker, "Grilichesian Breakthroughs: Inventions of Methods of Inventing in Nanotechnology and Biotechnology," National Bureau of Economic Research Working Paper No. 9825, July 2003.

Technology moves into manufacturing via an educated and trained workforce that is able to not only implement the new technology – here nanotechnology – but also innovate and develop new and refined processes and applications. This adaptive process extends to continuous improvements in the productivity of the new technology, maintaining competitive advantage. More than ever the adoption and refinement of new technology producing growth in productivity is linked to a simultaneous growth in human capital. This applies in particular to new industry clusters or to reinvigorating existing ones. For example, the application of nanotechnology to silicon wafer design will cost billions to change from current manufacturing technology to the new nano-based one. This investment involves building the machines to build the machines that will change how such circuits are manufactured and integrated into entirely new products. The failure to make the change at both levels could produce another California first: a silicon smoke stack industry. This suggests that workforce education and training, along with rapid advances in technology, produce a kind of dynamic competitive advantage for a region. This also implies that both higher education and workforce training curricula and structures must evolve, if not slightly outpace, the movement of technological innovations into the market place.

5.2.2 Need to Produce Multitudes of Start-Up Companies

Recent experience shows that new technology creates a new industrial sector by producing a multitude of small firms that coexist with other larger firms in a region. In addition to a highly trained workforce, Zhang[3] found that firms founded in Silicon Valley after 1990 created almost all of the job growth between 1990 and 2001. According to Zhang, the reason that Silicon Valley was able to outpace Boston and other areas was its quick access to venture capital. "On average, it takes 11.6 months for Silicon Valley's start-ups to complete their first round of venture financing – five months faster than the national average. Quicker access to capital is found in every major industry in Silicon Valley." This gives new companies a "first mover's advantage" in a very fast paced industry, which suggests that angel investors and venture capitalists must develop the capacity and specialized support networks to quickly vet and invest in new nanotechnology small companies. A second factor mentioned by Zhang is California's weak enforcement of agreements not to compete when leaving a company to start a new one. This factor was an important one that contributed significantly to Silicon Valley's success. Neither the role of early-stage investment nor of intellectual property rights will be examined in this chapter. They are mentioned to provide a more complete understanding of key factors that must come together at the right time to produce sector development and growth.

California already has a strong high-tech economy and a strong scientific base suggesting that we already have the necessary elements of a supportive infrastructure, including venture capital, to successfully move the technology out of the laboratories and into the private sector IF we are able to modify this structure in a receptive way. These structures facilitated and grew with the development of aerospace, information processing, the internet, biotechnology, and now micro electro mechanical systems (MEMS). Today strong research and high technology manufacturing clusters exist in San Diego, Orange, and Los Angeles counties and the Bay Area with an existing workforce training infrastructure in close proximity. The strategy to maintain competitive advantage is to continue to orient this research, training, and small technology business support infrastructure to fill the needs of the evolving scientific development and technology transfer process. For example, Michigan, once known as a manufacturing has-been, is rebuilding itself based on its strong engineering capabilities.

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[3] Junfu Zhang (2003). High-Tech Start-Ups and Industry Dynamics in Silicon Valley. San Francisco: Public Policy Institute of California, ISBN 1-58213-074-4.

5.2.3 The Global Productivity Race and Commercialization of Nanotechnology

It is helpful to view these general comments on dynamic competitive advantage from a global manufacturing competition perspective. According to an Alliance Capital analysis, manufacturing jobs are down globally, not just in the U.S. Manufacturing job data for 1995-2002 for the world's 20 largest economies show that only five gained manufacturing jobs. Between 1995-2002, 22 million jobs were lost globally, a decline of 11%. At the same time, global production jumped 30%.[4] Clearly, productivity improvements are creating competitive advantage for the winners.

The dynamic nature of competitive advantage can be seen by comparing direct labor and total manufacturing cost in semiconductors between the U.S. and China. According to Hatano, China's direct labor costs are less than a fifth of the U.S., but because of the capital intensive nature of semiconductors the total manufacturing cost is only 10% less, a gap that can be overcome with higher productivity. [5] The Chinese are aware of the importance of productivity. According to the Alliance Capital survey above, China's manufacturing job losses at 15% are double the average (7%) of the remaining third world countries for 1995-2002, suggesting that they too are improving productivity. [6] According to a June 24, 2000 China State Council Document: "With 5 to 10 years' effort…. Domestic integrated-circuit products will also satisfy most domestic demand and be exported as well while reducing the development and production technology gap with developed countries." This is not an empty threat. Andy Chatha, President of ARC Advisory Group, concluded from a recent trip to major Chinese industrial centers that China's automation business is "booming"– growing at 25% or 3 times its Gross Domestic Product (GDP) growth rate. Most major automation companies claimed to have landed at least one mega order in the range of $20-$40 million this year.[7] "Completely new facilities are being built in every industrial sector, including refineries, steel mills, and power, auto, and cement plants. Plus, China's trade balance gives it the money to invest in badly needed infrastructure." [8]

5.2.4 Lessons for California's Developing Nanotechnology Industry

The comparison between the U.S. and China holds important lessons for California. First, California has the advantage of an existing nanotechnology basic research capability and technology based infrastructure. However, this "older" infrastructure must be aligned to keep track with unfolding research and commercialization developments. There is a potential lag in that existing training institutions may be reluctant to shift resources from familiar sectors into a new one. Second, the rapid transfer of new nanotechnology research to the private sector via small nanotech start-ups may not be enough if the start-ups are not able to incorporate current production, just-in-time warehousing, collaborative design with the customer, and other productivity advances that are producing competitive advantage today. Third, other countries

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[4] National Coalition for Advanced Manufacturing (NACFAM) (2003). Manufacturing Jobs Down Worldwide. NACFAM Weekly November 10, 2003 Vol., 11, No. http://www.alliancecapital.com/.

[5] Daryl Hatano, Vice President, Public Policy, Semiconductor Industry Association (October 23, 2003). Trends in Manufacturing and High Tech Immigration – Ramifications for Maintaining Technology Leadership. Speech to the California Council on Science and Technology, Irvine, California.

[6] National Coalition for Advanced Manufacturing (NACFAM) (2003). Manufacturing Jobs Down Worldwide. NACFAM Weekly November 10, 2003 Vol., 11, No. http://www.alliancecapital.com/.

[7] Richard Noeth, Ty Cruce, and Mat Harmston (2003). "Maintaining a Strong Engineering Workforce," an ACT Policy Report.

[8] NACFAM Weekly November 10, 2003.

and, as we shall shortly see, other states are also seeking to achieve competitive advantage in both nanotechnology development and production. At least in China's case, this gap could close in 10 to 15 years IF they are able to establish a basic nanotechnology science capability AND develop commercial technology infrastructure. In today's information economy, new discoveries and production technologies are quickly communicated around the world reducing the time that the original discoverers have to capitalize on the results and gain a return on their investment.

5.3 What Products is Nanotechnology likely to Produce and what skills is the workforce likely to need over what time period?

5.3.1 Potentially Affected Industries and Possible Nanotechnology Products

Nanotechnology is predicted to have varying impacts by 2007 on different industries as shown in Figure 5.1. The most significant nanotechnology revenue generating sector could be healthcare, followed by telecommunications, chemicals, and computers and electronics. Probably the most significant lesson to be taken away from the diagram is the broad and varying range of impacts and revenues that could occur at varying rates across multiple industries. The projection also suggests that there may be significant market development in as short a time as four years.

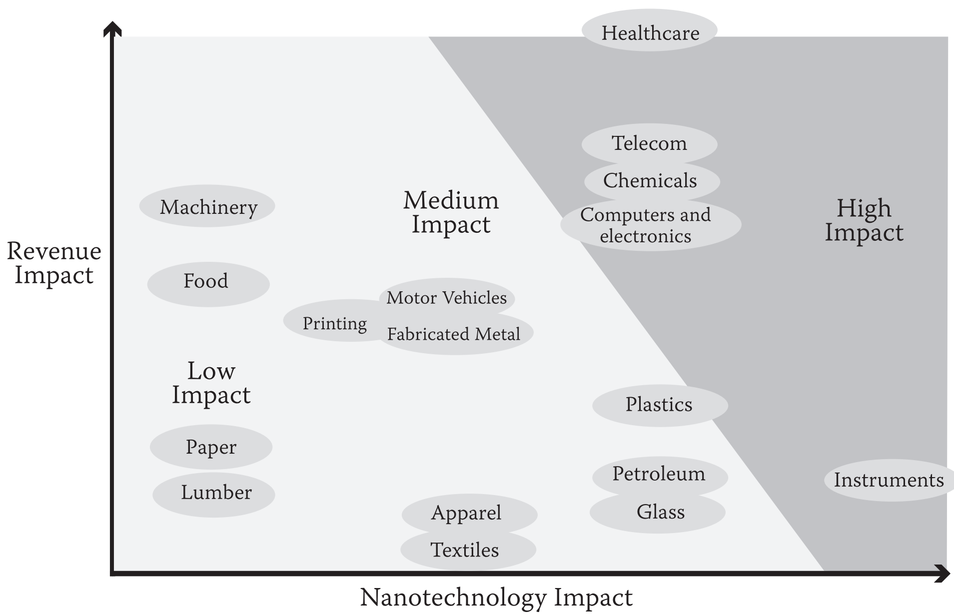

Figure 5.1: Nanotechnology's Probable Business Impact in 2007
Source: Larta, 2003

Nanotechnology applications that require the development of new skills might include producing: photovoltaics; hydrogen fuel storage; fuel cells; batteries and super capacitors; photocatalytic reductions of carbon dioxide to produce methanol and other liquid fuels; direct photoconversion of light and water to produce hydrogen fuel; super-strong, light-weight, low-cost light-harvesting materials; electronics; high-current cables; thermochemical catalysts to generate hydrogen fuel from water; robotics with artificial intelligence; materials and coatings for deep drilling; lighting to replace incandescent and fluorescent lamps; microscopic probes for planetary exploration or for special earth environments; biosensors and detectors and nanopore devices for detecting particular types of DNA, RNA and other biological materials; personalized forms of molecular medicine; vision chips for the blind and other medical devices for direct implantation; new nanocrystal coatings and nanocomputing "smart" surfaces; and a new crop of structural plastics, organic resins and nanopowders.

A limited number of nanotechnology products have made their way to the market. Some are listed in Table 5.1.

Nanotechnology Products on the Market

- GMC Safari nanocomposite step from Southern Clay
- Babolat tennis rackets using nanotubes
- Nucelle sunscreen using titanium dioxide nanoparticles from Nanophase
- Wilson Double Core tennis balls using nanomaterials from Inmat
- Duravit sinks and toilets using nanocoatings from Nanogate
- Eddie Bauer khaki pants using molecular textile coatings from Nano-Tex
- GAP, Old Navy, and Claiborne shirts from Nano-Tex
- Maui Jim sunglasses with nanocoatings from Nanofilm
- Nanowax DERAX ski wax used by Olympic ski teams from Nanogate
- Kodak EasyShare LS633 using nanoenhanced OLEDs
- Evidots (Quantum Dots) for medical imaging from Evident Technologies
- Nanox ceramic nanocoatings on Navy ship hulls from Inframat
- L'Oreal nanocapsules in cosmetics
- Non-stick, germicidal nanocoating in Audio Service hearing aids from Germany's Institute of New Materials

Table 5.1: Nanotechnology Products in the Market
Source: "*The Nanotech Report 2003*," Lux Capital

5.3.2 Mass Nanoproduction Problems are Waiting to be Solved

The difficulty of mass-producing nano products remains one of the biggest issues the industry faces today. Building nanotechnology production lines costs tens of millions of dollars. For example, to recoup development and manufacturing costs, carbon nanotubes sell for $600 per gram, or about a quarter-million dollars a pound. Such high costs have prevented the established and reliable supply of nano products limiting their successful mass commercialization. Often, nanotechnologies are proven in prototype, but are not easily integrated into new mass producible devices.[9]

It is very difficult to predict what stages the emerging nanotechnology industry will go through as it emerges. These efforts must move quickly from the laboratory into new start-ups. Interestingly, "investors are jumping in less than five years after the formation of the National Nanotechnology Initiative (NNI), not twenty-five years after the development of a specific military application." [10] These

[9] Rohit Shukla, Victor Hwang, Ketaki Sood, James Klein, Andrew Cohn (Larta) (2003). Nanotechnology What to Expect: A Larta White Paper. Los Angeles: Larta.

[10] Basmat Parsad, and Elizabeth Farris (2000). Occupational Programs and the Use of Skill Competencies at the Secondary and Postsecondary Levels, 1999. NCES 2000-023. U.S. Department of Education. National Center for Educational Statistics, Washington, D.C.: U.S. Government Printing Office.

developments suggest that venture and angel capital might be available early on for startups repeating the process seen in Silicon Valley. The catch is whether a trained research and technician workforce will also be available to enable the production of a dynamic competitive advantage.

5.4 Are Nanotechnology Curricula being developed for higher education and technicians?

A key problem will be simply attracting students to nanotechnology education, research, and training programs generally. The image of manufacturing of whatever kind is negative and highly outdated, particularly for high-school students and their parents.[11] This broad range of impacts also suggests that the technical workforce must have a broad background encompassing an understanding of the principles of biology, physics, and chemistry as well as the engineering principles of design, process control, and yield.[12] A second challenge will be to create the required broad interdisciplinary programs themselves. A third problem will be to make nanotechnology measuring and other laboratory equipment available for training researchers and technicians. The latter will need access to manufacturing equipment used by industry. For example, the atomic force microscope greatly broadened the range of materials which could be viewed at the atomic scale and enhanced the ability to manipulate individual atoms and molecules including those involved in cellular processes.[13] All three problems must be simultaneously addressed.

The fact that the nanotechnology industry cluster is so diverse, with each industry at varying stages of development makes it very difficult to determine what general workforce skills are necessary. Still, in all cases research must be done, process and product development carried out, and products manufactured, marketed and sold to consumers. Each activity requires related but different educational and technical skill sets.

The National Nanotechnology Initiative calls for "…new types of education and training that lead to a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology. The proposed initiative will leverage the existing strong foundation of nanoscience and engineering in the U.S.…".[14] In 2002, the Nanotechnology Undergraduate Education (NUE) was formed as part of NNI to develop undergraduate courses and to demonstrate the science of nanotechnology to K - 12 students and teachers. This new program was directed at universities that emphasized teaching excellence.[15]

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11 National Association of Manufacturers (2001). The Skills Gap (2001): Manufacturers Face Persistent Skills Shortages in an Uncertain Economy.

12 Stephen Fonash (2001). Education and Training of the Nanotechnology Workforce. Journal of Nanoparticle Research 3: 79-82.

13 Darby, Michael R., and Lynne G. Zucker, "Grilichesian Breakthroughs: Inventions of Methods of Inventing in Nanotechnology and Biotechnology," National Bureau of Economic Research Working Paper No. 9825, July 2003.

14 National Science Foundation, Committee on Technology (2002). Societal Implications of Nanotechnology and Workforce Education and Training in the National Nanotechnology Initiative, Appendix A 5. Washington, D.C., February 2000.

15 Mel Mendelson, Gary Kuleck, James Roe, Jeff Sanny, John Bulman, Rafiq Noorani (2003). Integration of the Basic Sciences and Engineering through Nanotechnology. International Conference on Engineering Education, July 21-25, 2003, Valencia, Spain.

The industry-government-academic partnerships created by the NNI and its affiliated programs could focus the emergence of new startups around the five National Nanofabrication Users Network (NNUN) centers, particularly in areas with a strong high-tech workforce.[16]

In 2002, the American Society of Mechanical Engineers (ASME) proposed significant changes to the engineering curriculum: (a) educate students in nanotechnology, and (b) offer biology in addition to the required physical science courses.[17] These recommendations are consistent with the cross-disciplinary nature not only of nanotechnology basic research but also of its applications.

As radically new technologies are developed, new social, economic, ethical, legal, environmental, and workforce development issues can also arise. These developments will also require cross-disciplinary training between the physical and social sciences.

5.4.1 Research and Graduate Education

Today, about 27% of employees in the manufacturing sector have a baccalaureate degree.[18] A significant portion of the remainder have two-year community college degrees or industry acceptable skill certification. These proportions will probably increase in the more technology driven environment of nanotechnology.

Nanofabrication requires a basic understanding of physics (wave functions, quantum mechanical tunneling, and atomic force probes) and chemistry (tailoring molecules, functionalizing surfaces and 'hooking' molecules together) which govern the nanoscale world. Self-organization based on biological models will govern 'bottom-up' nanofabrication. The difficulty is that college curricula are usually highly specialized with few opportunities to move between or even experience different scientific disciplines. Currently, despite ASME, engineering education is moving away from exposure to the hard sciences including physics (quantum mechanics for example) and often does not require a course in biology.

Motivating college students to become involved in nanotechnology is an important objective. Mendelson and others at Loyola Marymount[19] have developed a sophomore curriculum that integrates science, engineering and ethics. The course focuses on how nanotech might improve the human body. Hands-on experiments are run in class.

Graduate level nanotechnology laboratory experience that cuts across disciplines is necessary but difficult to get for graduate students. Most are restricted to the research that their major professor is carrying out in his or her laboratory. Recently, 46 out of 250 total National Defense Science and Engineering Graduate scholarships were for graduate research at the nanoscale, and of the 189 projects of the multidisciplinary Research Program of the University Research Initiative, 17% focused on the nanosciences in 2000.

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16 Basmat Parsad, and Elizabeth Farris (2000). Occupational Programs and the Use of Skill Competencies at the Secondary and Postsecondary Levels, 1999. NCES 2000-023. U.S. Department of Education. National Center for Educational Statistics, Washington, D.C.: U.S. Government Printing Office.

17 Mel Mendelson, Gary Kuleck, James Roe, Jeff Sanny, John Bulman, Rafiq Noorani. Integration of the Basic Sciences and Engineering through Nanotechnology. International Conference on Engineering Education, July 21-25, 2003, Valencia, Spain.

18 Elias Lopez (2002). The College Age Group and Scholastic Performance in California. Sacramento: California Research Bureau.

19 Ibid.

5.4.2 Technician Training

"Creating a properly prepared nanotechnology technician workforce, which is essential for manufacturing, is probably the most demanding educational task of all." [20] For example, unique skills are required to actually design the products that nanotechnology makes possible and can produce. Pisano states: "I triple-emphasize…that what's missing are people who know how to DESIGN things at the micro and nanoscale. The efforts of private industry to create low-level nanoengineers cannot address that lack of designers. That is the essential problem." [21]

Like four-year and graduate schools, two-year colleges must provide their students with a broad scientific and technological background including various applications of nanotechnology. This broad range of impacts also suggests that the technical workforce must have a broad background encompassing an understanding of the principles of biology, physics, and chemistry as well as the engineering principles of design, process control, and yield.[22] Hands-on exposure to 'top-down' and 'bottom up' nanofabrication processing is also necessary. The whole point is to create a workforce that can use similar skill sets to migrate from industry to industry to follow scientific and production breakthroughs. Fonash suggests that this workforce must not be trapped in one industry, but must be able to apply nanotechnology to industries as diverse as biomedical applications, MEMS, pharmaceuticals, opto-electronics, and information storage.

Problems with obtaining workers with the right technical skill sets are already apparent. Today, 80% of U.S. manufacturers experience a moderate to serious shortage of qualified job candidates to carry out such activities as product design and process development.[23] Technical competency is only one of the three employee qualities that Southern California manufacturers, for example, are looking for. [24] These qualities include work ethic, teamwork, and problem solving – all areas that will be at a premium for bringing new nanotechnology processes into production. Familiarity with Total Quality Management, computer aided design, Computer Integrated Manufacturing, and other computer systems critical to product design, tools to share drawings/designs with suppliers/customers, business process design,[25] and a networked manufacturing system (including links to global supply chains) were also identified as critical in the current manufacturing world and will probably continue to be necessary requirements as nanotechnology comes on board. Even so, a recent NAM survey[26] found that about 64% of small and medium sized manufacturers spent less than 2% as a percentage of sales on training.

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[20] Stephen Fonash (2001). Education and Training of the Nanotechnology Workforce. Journal of Nanoparticle Research 3: 79-82.

[21] Brian Pandya (2003). NANOTECHNOLOGY WORKFORCE PIPELINE CHALLENGES: A Current Assessment and The Future Outlook. Washington Internships for Students of Engineering for the summer 2001 program, The American Society of Mechanical Engineers.

[22] Stephen Fonash (2001). Education and Training of the Nanotechnology Workforce. Journal of Nanoparticle Research 3: 79-82.

[23] National Association of Manufacturers (2001). The Skills Gap (2001): Manufacturers Face Persistent Skills Shortages in an Uncertain Economy.

[24] Flintridge Consulting (2001). Manufacturing Needs Survey Results. Pasadena, CA.

[25] National Association of Manufacturers, Manufacturing Institute, and Deloitte and Touche (2003). Keeping America Competitive. Washington D.C.

[26] National Association of Manufacturers (2003b). 2003 NAM Small Manufacturers Operating Survey. http://NAM SME 2003 survey.htm.

5.4.3 Experimental and Hands-On Training Facilities

Access to properly equipped, up-to-date nanotechnology and related technology laboratories is essential for both research and technician training. As mentioned above, the nanotech workforce will have to have direct experience with new instruments that are too expensive to provide each classroom. In some cases, industry may be willing to donate equipment or to permit use of their equipment on site. The Economic and Workforce Development Program of the California Community Colleges has worked closely with multimedia and other industries in just this way.

The National Science Foundation (NSF) is also addressing the facilities problem. A National Nanofabrication Users Network (NNUN) has been created with shared nanotechnology facilities or resources open to users across the nation.[27] The Penn State NNUN site with the latest nanotechnology processing equipment is an example of how a group of colleges can use a single high cost facility to train two- and four-year college students.[28] The Pennsylvania Nanofabrication Manufacturing Technology (NMT) Partnership joins together the state of Pennsylvania, the Penn State site of the NSF National Nanofabrication Users Network, industry, and two year colleges. The program provides a one-semester, hands-on experience for community college students. The semester experience is part of the two-year colleges' nanotechnology technician training leading to a two-year NMT degree. Industry offers NMT degree graduates jobs with salaries from \$35,000–\$52,000 per year. Only two years old, the program produces 60 students per year. The NMT project also has a high school outreach component which has also proven itself.

5.4.4 Occupational Health and Safety

Many of the new powders, coatings, and other materials may have unique, even biologically active properties that will require rethinking occupational and safety standards in the workplace. The capacity to work in special environments using special protective equipment may be necessary. Also, "the potential implications of human performance enhancement and the possible development of nonhuman intelligence" (See chapter 6, p. 99) to increase productivity by improving the worker-technology interface may create significant health, safety, personal stress issues (see NSF discussion on virtual reality and manufacturing implications).

5.5 How well prepared is California's workforce to address nanotechnology's scientific and technical challenges?

Clearly, highly educated workers are critical to the growth of California's high-tech industries including nanotechnology. The percentage of workers with high-tech jobs in California is nearly 50% higher than the national percentage. In addition, the state has held close to 11% of the total U.S. employment for two decades, but 15-18% of U.S. high-tech employment over the same period.[29] Moreover, the national projected need for skilled workers is 10 million by 2020.[30] A very significant number of these workers could be involved in nanotechnology related occupations. Lux Capital, a venture capital investment firm specializing in nanotechnology, estimates that "40,000 U.S. scientists are capable of working in nanotech. 800,000 U.S. workers (40% of worldwide total)

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[27] Stephen Fonash (2001). Education and Training of the Nanotechnology Workforce. Journal of Nanoparticle Research 3: 79-82.

[28] Ibid.

[29] California Council on Science and Technology (2002). Critical Path Analysis of California's Science and Technology Education System. Sacramento: California Council on Science and Technology.

[30] National Association of Manufacturers, Manufacturing Institute, and Deloitte and Touche (2003). Keeping America Competitive. Washington D.C.

will be needed to support NSF predictions of a $1 trillion nanotech industry by 2015. In the past four years, more than 1,700 jobs have been created from venture capital funding in nanotechnology." [31]

5.5.1 Changing Demographics

The future growth of the workforce and its composition is intricately linked to the state's changing demographics. One element of this change is the highly skilled but ageing baby boomers who will be retiring within the next ten years.[32] A second demographic change is the tremendous growth of the Latino and Asian populations over the last 30 years. The California educational system and economy are just beginning to feel the full impact of this transformation. These groups are young and are just entering the higher education system but have not entered the labor force. Lopez, in a recent California Research Bureau study[33] notes:

> "In the case of Latinos, the most demographically dynamic population, close to 40 percent of the population are children. In the next decade, for instance, there are going to be over four million Latino children moving through the K-12 system and into the labor force. With Latinos comprising the largest demographic group under age 18, there will be a significant change in the labor force over the next 10 to 20 years."

Several serious implications for the nanotechnology workforce emerge from these changes alone. First, there will be a substantial turnover in the workforce; an older highly skilled generation must be replaced by an equally if not better skilled younger one. Second, nanotechnology development timelines suggest that a significant flow will develop in ten years producing a sizeable market. This new, younger workforce must be available to fill in the expanding nanotechnology job market if the development of nanotech is not to be stunted. Third, the development of commercial nanotechnology is limited by a fourteen year lag between a basic research discovery and its commercialization. Scientists need to be educated and trained now to make the breakthroughs that will generate the products ten years from now.

5.5.2 African Americans and Latinos are not Prepared for College

Generally, California's Latinos, African Americans, American Indians and Pacific Islanders are disproportionately unprepared to enter four-year universities. As Figure 5.2 shows these groups are among the least likely to complete the requisite courses for entrance into a four-year university. Of those groups least prepared, the two largest groups are Latinos and African Americans. Right from the beginning there are problems. These problems extend into scientific and engineering education.

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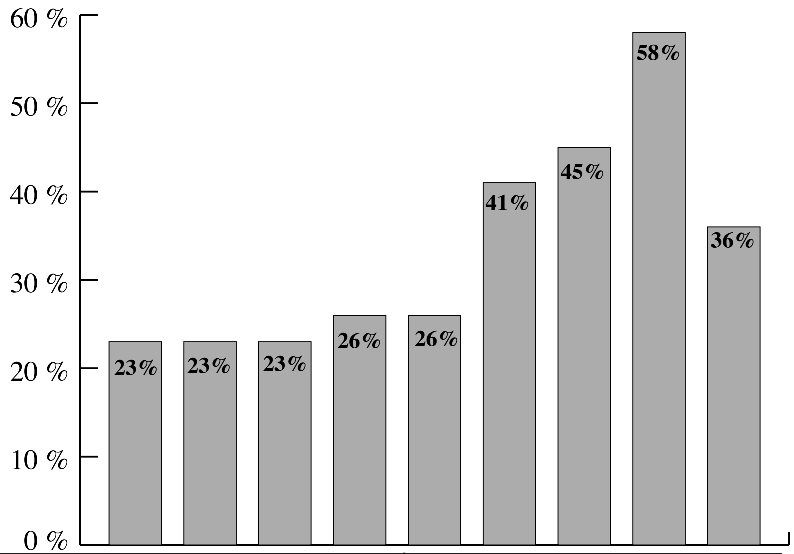
31 Lux Capital (2003). The Nanotechnology Report, 2003. http:/www.luxcapital.com/nanotechreport/.

32 National Association of Manufacturers (2003). 2003 NAM Small Manufacturers Operating Survey. http://NAM SME 2003 survey.htm.

33 Elias Lopez (2002). The College Age Group and Scholastic Performance in California. Sacramento: California Research Bureau.



	Multiple Races	Latino	American Indian	African American	Pacific Islander	White	Filipino	Asian	Total
High School Graduates	935	103,795	2,734	22,474	2,052	139,228	10,229	34,677	316,124
HS Grads with UC/CSU Requirements	232	23,772	632	5,874	537	56,553	4,654	20,235	112,469
% of HS Grads with UC/CSU Requirements	23%	23%	23%	26%	26%	41%	45%	58%	36%

Figure 5.2: High School Students Graduating with the Required Courses for a Four-Year University, 2001
Source: California Research Bureau

5.5.3 The Central Role of Immigrants in Filling the Global Education Gap

Immigrants are playing a very important role in the development and funding of new high technology sectors in California and around the world. Professional/technical skilled immigrants account for one-third of Silicon Valley's workforce. Immigrant-run companies are important to the development of high-tech industry clusters. For example, in 1998 immigrant-run companies in Silicon Valley accounted for $26.8 billion in sales and 58,282 jobs. This population was attracted to both the quality graduate education available in California, and to the opportunity to establish a business in the area. [34]

Workers with master's degrees are in high demand as shown by the numbers of H-1B workers that hold them.[35] Over 42,000 master's degrees were granted in California in 2000. However, over 35% of all master's degrees were awarded to non-resident aliens, indicating that fewer Californians are pursuing graduate degrees in science and in engineering. The availability of science and engineering Ph.D.s in California's colleges and universities, and its private sector, is also highly related to California's current nanotechnology research domination. California granted approximately 5,300 Ph.D.s in 2000, of which 40% were in science and engineering.[36] Non-resident aliens earned over 30% of the science and engineering degrees. Lux Capital[37] estimates that:

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34 AnnaLee Saxenian (2002). Silicon Valley's New Immigrant High-Growth Entrepreneurs. Economic Development Quarterly, Vol. 16, No. 1, February 2002.

35 California Council on Science and Technology (2002). Critical Path Analysis of California's Science and Technology Education System. Sacramento: California Council on Science and Technology.

36 Ibid.

37 Lux Capital (2003). The Nanotechnology Report, 2003. http:/www.luxcapital.com/nanotechreport/.

> "Asia is particularly competitive in nanotechnology. Asian companies are funding research as well as striking deals for intellectual property from U.S. universities. At the current rate, by 2010, 90% of all physical scientists will be Asian, with 50% of them practicing in Asia."

Nanotechnology degree programs are offered or are being designed at several leading California institutions, including the University of California, Los Angeles (UCLA), Stanford University, and the California Institute of Technology (Caltech). However, it is too soon to determine degree trends from these programs.

California's dependency on highly educated and skilled immigrant workers mirrors a global migration phenomenon among advanced economies. Movement of science and technology workers tends to aid knowledge transfer rather than act as a brain drain. This is a significant point showing that nanotechnology, like biotechnology, is a global industry cluster with information being moved from place to place by its skilled workforce.

Nanotechnology is a top priority for many countries, especially Japan and Europe, and many countries are actively recruiting foreign students into their universities. In some European nations, procedures for switching from student to work visas are being expedited to retain skilled researchers and workers.

In 2001, the United States increased the number of temporary immigration visas allowing 195,000 professional and skilled workers to enter the country for temporary work. Germany allows computer and technology specialists to enter the country and work for up to five years. France and the United Kingdom have simplified procedures for admitting computer specialists and skilled workers in designated shortage occupations. Similar efforts will probably be made to attract nanotechnology researchers and technicians as various sectors take off.

5.5.4 Scientific and Engineering Education

Since nanotechnology is multidisciplinary, understanding the general status of S&E education in California gives a good picture of the preparation necessary to enter the nanotechnology workforce. Noeth, Cruce, and Harmston [38] used ACT scores and associated materials to assess how prepared high school students are nationally to pursue science and engineering degrees. They found that nationally the number of students who plan to major in engineering upon college entrance has continued to decrease. Of the 1.1 million graduating high school students in 2002 who completed the ACT Assessment and planned to go on to a four-year college major, 52,112 planned to major in engineering (well below the high of 67,764 students in 1993). The representation of potential engineering majors among ACT test takers steadily decreased too, reaching a low of 5.5% in 2002 compared to a high of 8.6% in 1992. There was also a significant drop in the number of female students (9,345) who planned to major in engineering, representing a twelve-year low of 18%. Many of these students (40%) say that they need help in deciding their educational plan suggesting that the "bad" image that manufacturing (including nanotechnology) has could influence their decision.

[38] Richard Noeth, Ty Cruce, and Mat Harmston (2003). "Maintaining a Strong Engineering Workforce," an ACT Policy Report.

5.5.5 Ethnic Minority Preparation for Majors in Science and Education is Weak

Noeth, Cruce, and Harmston [39] also studied the number and level of preparation of underrepresented ethnic students preparing for an engineering career. It is worth quoting their findings at length given California's dependence on the future development of ethnic minority engineers, including those in the nanotechnology field.

> [Nationally,] [b]etween 1991 and 2002, the representation of African American and Hispanic students increased; the representation of American Indian students remained fairly stable. Together, these groups represented 22.2% of all potential engineering majors from the high school class of 2002 (African Americans, Hispanics, and American Indians represented 14.1%, 6.9%, and 1.2%, respectively). The percentage of potential engineering majors among various minority groups improved over the past 12 years, but the increase was due in large part to a decrease in the number of Caucasians who planned to major in engineering. In fact, the number of minority students planning to major in engineering has dropped. The actual number of African American and American Indian engineering majors was lower in 2002 than in 1991 (African Americans reached a low of 6,993 in 2002).
>
> For minority students there is a substantial misalignment between aspirations and preparation. Although many were very sure of their choice to enter an engineering major, many did not complete core coursework requirements and had taken only basic mathematics and science course sequences. This included lower levels of course taking in calculus and physics.

5.5.6 Preparation to Pursue Science and Engineering Degrees in California is Weak

CCST has projected that the college participation rate will grow worse due to increasing numbers of Latinos and African Americans in the K-12 system. [40] Only about 5% of Latino 9th graders complete high school with the necessary preparation to go on to college. This study also found that of all students graduating from high school in California, the shortfall in preparation for science and mathematics was found to be particularly acute. In addition, CCST found that California is not producing enough baccalaureates in science and engineering. [41] The reasons for this include inadequate high school preparation, student difficulties in passing core science and engineering courses, and limited tutoring capacity which may not be getting to the students who need it. There is no reason to think that production of nanotechnology degrees will be different.

A number of efforts have been made to address these shortcomings. For example, a study by Seymour [42] found that high school students were overwhelmingly positive about undergraduate research experience in a functioning research laboratory. Williams, [43] after reviewing multiple outreach programs teaming practicing scientists with high school students, found similar positive results. This study also emphasized the importance of developing appropriate administrative relationships to be effective.

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39 Richard Noeth, Ty Cruce, and Mat Harmston (2003). "Maintaining a Strong Engineering Workforce," an ACT Policy Report, p.9.

40 California Council on Science and Technology (2002). Critical Path Analysis of California's Science and Technology Education System. Sacramento: California Council on Science and Technology.

41 Ibid.

42 Elaine Seymour, Anne-Barrie Hunter, Sandra L. Laursen, and Tracee DeAntoni (2002).

43 Valerie Williams (2002). Merging University Students into K–12 Science.

5.5.7 Technician Training

Well trained technicians with community college associate degrees are necessary to run various test instruments in laboratories and manufacturing processes. Lopez has identified the number of associate degrees awarded by ethnicity in California (Figure 5.3). Data are not available by major or for technicians trained at private sector trade schools.

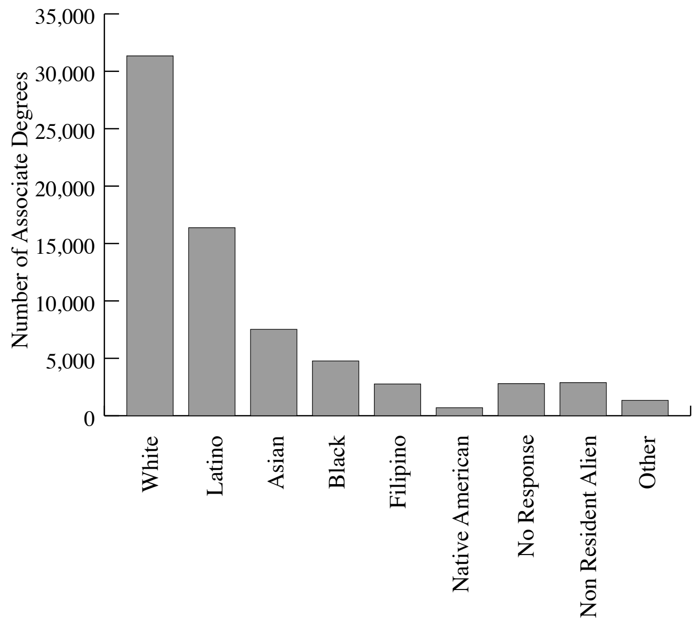

Figure 5.3: Number of Associate Degrees Awarded in California by Ethnicity (2002)
Source: California Postsecondary Education Commission, www.cpec.ca.gov

CCST, in their *Critical Path Analysis of California's Science and Technology Education System* found that the state's community colleges were not producing enough S&E certificates and associate degrees.[44] Transfers to four-year colleges were also too low. Campus scientific instructional capacity and facilities such as laboratories were resource limited. Counseling services to guide students through the necessary scientific and preengineering course preparation were cut in 2002. These are severe problems given that community colleges are the gateway for many underrepresented students to enter the higher education system. Transfer students perform quite well, representing a real opportunity to improve skills and to complete lower division course requirements at a reasonable cost.

The educational level of California's general workforce is not acceptable for developing high technology industries such as nanotechnology. Nearly one in five adult workers (2.5 million) in California lacks a high school degree. Of these, 73% are Latino.[45] This suggests that it will be necessary to attract and retrain workers from other high technology sectors who can already meet nanotechnology technician educational requirements or to rely on immigrants as California's IT sector has.

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[44] California Council on Science and Technology (2002). Critical Path Analysis of California's Science and Technology Education System. Sacramento: California Council on Science and Technology.

[45] Elias Lopez (2000). "Less-Educated Workers in California: A Statistical Abstract." Sacramento: California Research Bureau.

5.5.8 Continuing Education On and Off-Campus

Continuing education on and off-campus provides various types of credentials, certificates, and certifications of job related competencies in various fields. Such skills are critical for not only moving into a new technological field in a new industry cluster but also for moving up and across fields as will be characteristic of nanotechnology. This training sector may be very important for the future development of the commercialization of nanotechnology. For example, the California Community Colleges Economic and Workforce Development Program already has a statewide workforce training system in place. Its enabling legislation supports development of a nanotechnology initiative.[46]

> THE LEVEL OF EDUCATION OF CALIFORNIA'S GENERAL WORKFORCE IS NOT ACCEPTABLE FOR DEVELOPING HIGH TECHNOLOGY INDUSTRIES SUCH AS NANOTECHNOLOGY.

Available data shows that most start-up and small high technology manufacturing companies do not have the resources to train their own workforce (little is known about biotechnology or MEMS start-ups). A 2001 National Association of Manufacturers survey found that: "Sixty-one percent of the respondents said they spend one percent or more of their payroll on training for both hourly and managerial employees; one third (33 percent) spent two percent or more; and 17 percent spend three percent or more. Most training (62 percent) is done in-house. The top three sources for outside training are vocational/technical schools (46%); business associations (46%) and community colleges (45%)."[47] A California survey of 3,000 small manufacturers made similar findings. This survey also noted that identifying and adopting new technology, including information technology, were critical issues for Los Angeles Area manufacturers.[48] Taken together, training and technology adoption issues suggest that it may be hard for existing manufacturers to migrate to nanotechnology related processes without considerable outside help.

5.5.9 Nanotechnology Non- and Not-For-Credit Courses

There is little summary data available about the number of non- and not-for-credit post-secondary and post baccalaureate education courses offered by the California Community Colleges, California State University (CSU), University of California (UC) or the private training sector. Reliable data are also lacking on the size of the market for such training. Table 5.2 shows that in 1997-98 there were 9,632 non-degree granting institutions in the United States.

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[46] California Community Colleges Chancellor's Office (CCCCO)(2002). Community Colleges Economic Development and Workforce Training Program Annual Report 2000-2001. Sacramento: California Community Colleges Chancellor's Office.

[47] National Association of Manufacturers (2001). The Skills Gap (2001): Manufacturers Face Persistent Skills Shortages in an Uncertain Economy.

[48] California Manufacturing Technology Center (1999). Challenges & Barriers that California Manufacturers Have in their Growth. Los Angeles: California Manufacturing Technology Center.

Type of Institution	Total Number	Percent Title IV eligible
All Institutions	9,632	71%
Degree Granting	4,495	91%
Four-Year	2,664	87%
Two-Year	1,829	97%
Non-Degree Granting	5,137	53%
Four-Year Certificate	146	39%
< Four-Year Certificate	4,986	53%
Public	530	86%
Private nonprofit	629	46%
Private for-profit	3,827	50%

Table 5.2: In the U.S. Non-Degree Granting Institutions Outnumbered Those Conferring Degrees Source: Carnevale and Desrochers [49]

Less than two-year institutions tend to have stronger ties with industry, with 84% of a national sample indicating that all of their occupational programs prepare students to earn industry-related credentials (company certificates, industry/trade certificates) compared with only 28% of two-year community colleges. Such credentials may be important to show competency in operating new nanotechnology instruments and manufacturing processes. Data is not available for four-year colleges and universities but is probably less than that for community colleges.[50] In terms of more nanotechnology related training for two-year schools, 43% of technical and 66% of mechanical occupational training courses offer industry related certificates compared to 85% and 89% respectively for less-than-two-year schools.

5.5.10 California's Community Colleges Economic and Workforce Development Program

California's Community Colleges, through their Economic and Workforce Development Program, provide a very significant portion of off-campus certificate and non- and not-for-credit education to California's workers in high technology industries. This statewide system has proven its capability to reposition elements of its training operations to meet emerging industry needs such as those that will accompany nanotechnology technicians' emerging needs.

The Economic and Workforce Development Program provides services in ten areas including the following in high technology: Advanced Transportation Technologies (fuel cells for example), Applied Competitive Technologies (manufacturing), Environmental Technology, Multi-media (includes information technology and programming), and Biotechnology. Outcomes are impressive relative to the number of workers trained, businesses served, and private sector resources leveraged. For example in 2000-01, the California Community College System:[51]

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[49] Anthony Carnevale and Donna Desrochers (2001). "Help Wanted…Credentials Required: Community Colleges in the Knowledge Economy". Washington, D.C.: Educational Testing Services and the American Association of Community Colleges.

[50] Basmat Parsad, and Elizabeth Farris (2000). Occupational Programs and the Use of Skill Competencies at the Secondary and Postsecondary Levels, 1999. NCES 2000-023. U.S. Department of Education. National Center for Educational Statistics, Washington, D.C.: U.S. Government Printing Office.

[51] Mel Mendelson, Gary Kuleck, James Roe, Jeff Sanny, John Bulman, Rafiq Noorani (2003). Integration of the Basic Sciences and Engineering through Nanotechnology. International Conference on Engineering Education, July 21-25, 2003, Valencia, Spain.

- Used its FY 2000-01 budget of $45,172,000 (the budget was cut over 50% in FY 2003-04) to fund about $11 million in curriculum development, instructional packages, credit and non-credit programs, faculty mentorships, staff development, in-service training, and worksite experience and about $9 million for one-on-one counseling, seminars, workshops, and conferences that contribute to the achievement of the success of existing business and foster the growth of new business and jobs in emerging industry clusters.
- Leveraged $61,538,007 in donations and grants and an additional $28 million in industry match.
- Served 56,743 businesses, including 93,667 employees.
- Created $361 million in new jobs, and $212 million in additional salaries and wages.

5.6 Where are California's Regional Nanotechnology Industry clusters?

Nationally, over 700 companies are involved in nanotechnology. Since 1996, approximately 2,800 nanotechnology-related patent applications have been filed with the U.S. Patent and Trademark Office. The National Science Foundation predicts nanotechnology will grow into a $1 trillion a year industry. A survey by the NanoBusiness Alliance estimates that the nanotechnology industry already generates $45.5 billion each year and worldwide sales could reach a mammoth $700 billion by 2008. California has a good chance of capturing a substantial share of these sales if it can maintain and broaden its current competitive advantage.[52]

California is well suited to be the leading state in adopting and benefiting from nanotechnology. Southern California has a strong science and engineering base equal to that in the San Francisco Bay Area. The region is strong in manufacturing, biotechnology, medical devices and telecommunications. Northern California was the center of early development in semiconductors and biotechnology (See chapter 3).

5.6.1 San Francisco Bay Area

Silicon Valley is a knowledge-based economy already highly dependent upon cutting-edge businesses, world-class educational institutions, innovative research facilities, and an exceptionally skilled and knowledgeable workforce.[53] The North Valley Job Training Consortium (Nova), a regional workforce investment program, notes that Northern California, primarily Silicon Valley and the greater San Francisco Bay Area, already possesses the necessary infrastructure – including requisite leadership, knowledge, experience, physical space, and venture capital – involved with these related industries. The process of pulling together existing resources to establish the region as a nanotechnological power is, as many regional experts believe, "…primarily a matter of bringing together the key stakeholders and presenting the region as a cohesive entity with one voice and one mission."[54]

The Bay Area Science Innovation Consortium, which includes national laboratories, research universities, and leading private research firms, has launched strong nanoscience programs across several industries. New research centers have been established in the Bay Area including: The Molecular Foundry, the Bio-Nanotechnology Center and the Nanogeoscience Center in Berkeley, the NASA Ames Center for Nanotechnology and Stanford's Nanofabrication Facility in Silicon

[52] Rohit Shukla, Victor Hwang, Ketaki Sood, James Klein, Andrew Cohn (Larta) (2003). Nanotechnology What to Expect: A Larta White Paper. Los Angeles: Larta.

[53] Nova Workforce Board (2003). Nanotechnology: The Next Great Wave of Innovation. Nova workforce publications, publications@novaworks.org.

[54] Ibid.

Valley. There is also a great deal of work going on in other universities in the region. The Bay Area is well positioned given its base of skilled and highly trained researchers, state-of-the-art hardware and software resources, access to machines and instrumentation with unique capabilities, and its supportive start-up infrastructure.

Still not all is coming up roses. According to Chris Piercy, president and chairman of NCnano:

> "We're lucky because here in Silicon Valley we are the world leader in a number of technologies. …The downside to this is that there is still a lack of regional coordination, relatively speaking. Albany and Texas and other areas are pulling in billions of dollars to create foundries, develop infrastructure, help start-up companies, etc. Here in the Bay Area, we're home to dozens of nanotechnology start-ups, but unlike those other states, most of these start-ups are on their own until they raise their first major funding round. This means that as a region, we are also not able to fully leverage the already existing high-tech infrastructure Silicon Valley has, for the purposes of nanotechnology company development." [55]

> WE'RE HOME TO DOZENS OF NANOTECHNOLOGY START-UPS, BUT UNLIKE OTHER STATES, MOST OF THESE START-UPS ARE ON THEIR OWN UNTIL THEY RAISE THEIR FIRST MAJOR FUNDING ROUND.

5.6.2 Southern California

Nanotechnology has its roots in Southern California, and today the Los Angeles and San Diego Areas are still small-tech leaders. Presently, the most prominent industries in Southern California include biotechnology, microelectronics, and aerospace/defense industries; nanotechnology has significant promise for all of these. The region has already bred some of the most successful companies in the nanotechnology field.[56] As in Silicon Valley, the combination of top research universities, federal and corporate laboratories, and major corporations with expertise in materials science combine with a talented labor pool and a solid base of technically-oriented entrepreneurial talent (particularly in the San Diego region) to make Southern California an attractive center for nanotechnology research and development.

The California NanoSystems Institute, one of the four California Institutes for Science and Innovation funded in 2000, was set up as a joint venture between UC Los Angeles and UC Santa Barbara. With $100 million in state funding and a 2 to 1 match with non-state funds, this Institute is one of the most significant new nanotech research centers in the country. Moreover, UC Los Angeles and UC Santa Barbara have joined with UC Riverside to form the Center for Nanoscience Innovation for Defense (CNID), an alliance created to facilitate a rapid transition of research innovation in the nanosciences into applications for the defense sector.

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[55] Nova Workforce Board (2003). Nanotechnology: The Next Great Wave of Innovation. Nova workforce publications, publications@novaworks.org.

[56] Rohit Shukla, Victor Hwang, Ketaki Sood, James Klein, Andrew Cohn (Larta) (2003). Nanotechnology What to Expect: A Larta White Paper. Los Angeles: Larta.

The Los Angeles region is also home to Caltech and the University of Southern California (USC), top research institutions with strong nanotech programs; in fact one Caltech professor, James Heath, was recently listed as one of the country's top "Nanotechnology Power Brokers".[57]

In addition, companies such as Rockwell Scientific, Hughes Research Labs, and Amgen are pursuing nanotechnology research in the area, as well as the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (see Figure 5.4).

Since 2002, Larta, a think tank for technology businesses in the greater Los Angeles Area, has produced the prominent "Nano Republic" conference in Pasadena since 2002 in collaboration with Caltech, the California NanoSystems Institute, Rockwell Scientific Company, UCSB, UCLA, USC, and UCI. This national conference promotes technology transfer, highlighting recent developments in actual products and services based on nanotechnologies.[58]

Although the nanotechnology research and development community in Southern California is strong and Larta has positioned itself as the "technology alliance of Southern California," there are no regional initiatives such as NCnano or the Bay Area Nanotechnology Initiative.

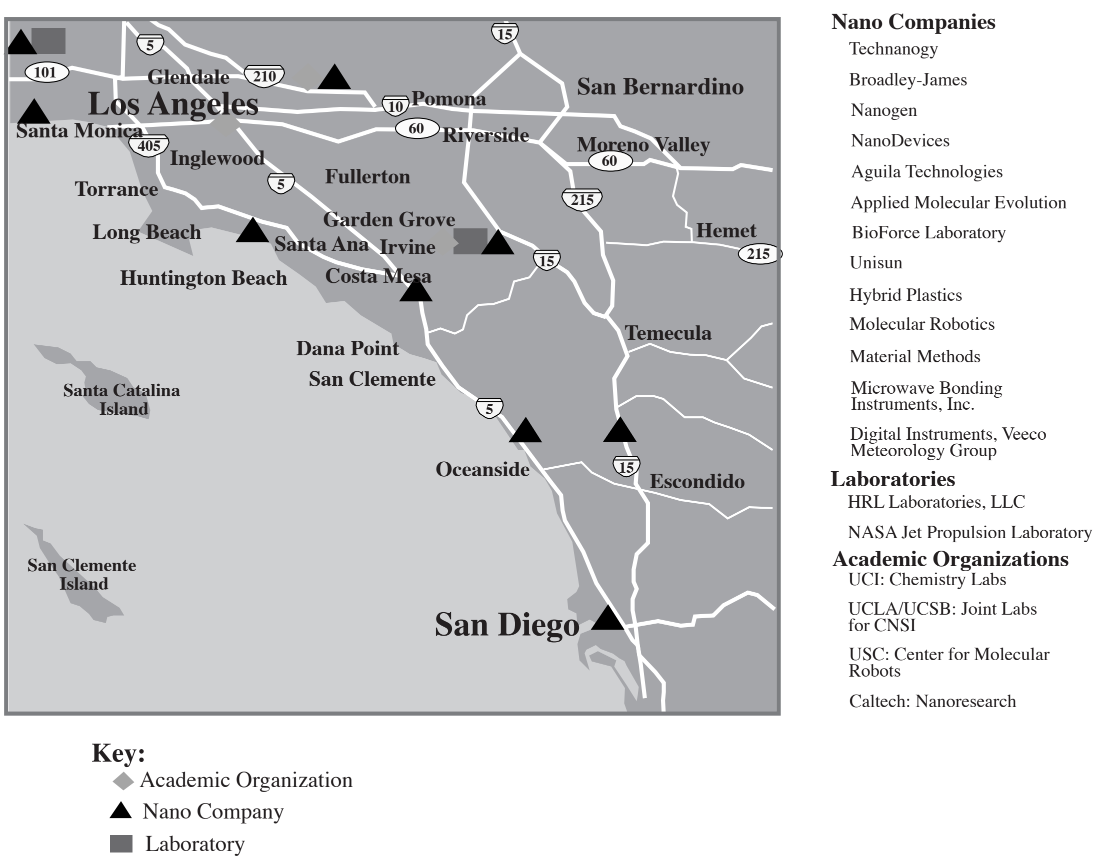

Figure 5.4: Nanotechnology Companies in Southern California
Source: Larta 2003

[57] Forbes/Wolfe Nanotech Report, March 2003.

[58] Rohit Shukla, Victor Hwang (2001). Nanotechnology Yellow Pages Industry Report and Directory. Los Angeles, Larta.

5.7 Who are California's global and state competitors and where are they in the race to generate competitive advantage relative to dominating the new industry?

5.7.1 Global Nation State Competitors

Nanotechnology research and development is occurring in over 50 nations. In 2002, Japan provided $750 million to fund nanotechnology, increasing from $135 million in 1998. The United Kingdom is running a close second, recently announcing $150 million in funding for nanotechnology research over the next six years. China, South Korea, and Canada have established their own nanotechnology initiatives much like the National Nanotechnology Initiative (NNI) in the U.S.[59] Denmark, Norway, and Sweden each has national nanotechnology initiatives and is forming regional consortia to pursue research and commercialization of the technology.[60] The Nordic countries, like our other global competitors, recognize the need for a university trained workforce.

> "In order to educate these people, Scandinavian and other universities offer Ph.D., Masters and even B.Sc. courses in nanoscience. In Denmark, Aarhus University and the University of Copenhagen offer B.Sc. courses. In MIC, Lyngby, they advertise many opportunities for Master's projects in nanoscience. There appears to be an international competition in nanoscience Master's courses, all competing for foreign students. Scandinavian universities do their best to participate in this competition for scarce natural science bachelors. In Finland, the Faculty of Mathematics and Science, University of Jyväskylä offers a Master's Program in Nanoscience. This two-year curriculum starts twice a year, for the first time [at the] beginning of 2003. The International Master's Program in Nanoscience educates interdisciplinary experts, who apply the knowledge and know how of physics, chemistry and biological sciences to the fast developing research and product development of the nanoscience. The Master's Program provides excellent basis for postgraduate studies." [61]

The relative competitive advantage of each nation has not been determined. However, important basic research is going on in each. It is also important to note that Japan's annual spending on nanotechnology R&D has consistently exceeded spending in the U.S. National Nanotechnology Initiative, and that Japan is already considered to be the world leader in some areas of nanotechnology R&D.

5.7.2 United States Competitors

According to Darby and Zucker (chapter 2 of this report), the following regions have strong nanoscience and nanotechnology capabilities: Los Angeles-Santa Barbara, San Francisco Bay, Boston, New York City, Philadelphia, Chicago, Champagne-Urbana, Raleigh-Durham, Atlanta, and Hartford-New Haven. However, these same regions are "not predictable by size, economy, or even overall strength of the science base." Data from other studies support these findings.

Stuart[62] identified and ranked the top ten states relative to their capacity for growing a new nanotechnology cluster by a cumulative score for research capacity, presence of related industries,

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[59] Organization for Economic Co-operation and Development (OECD) (2002). OECD Science, Technology and Industry Outlook 2002. Paris, France: OECD Publications Service.

[60] Nanoforum.org (2003). Nanotechnology in the Nordic Region. Nanoforum, European Nanotechnology Gateway.

[61] Ibid.

[62] Candice Stuart (2003). Choosing the right ensemble: Top 10 states are those that can fashion the perfect small tech outfit. Small Times, March/April.

available venture capital, rate of innovation, cost of doing business, and level of workforce training. California was ranked first, followed in order by Massachusetts, New Mexico, Arizona, Texas, Maryland, New York, Illinois, Michigan, and Pennsylvania (Figure 5.5).

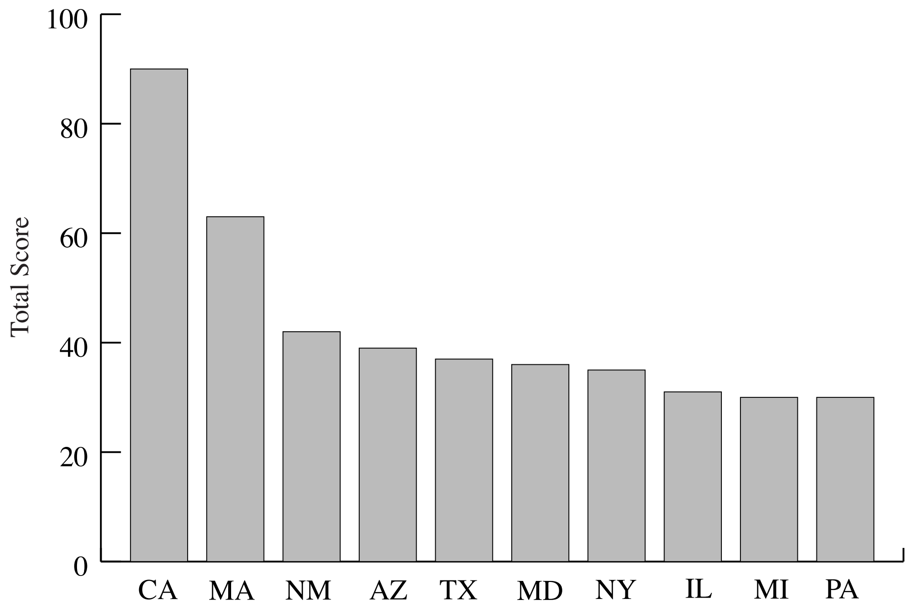

Figure 5.5: Ranking of Top Ten States by Degree of Favorableness to Small Technology Firms. Rankings are Based on Score between 100 and 1 Based on: Research (20%), Industry (20%), Venture Capital (20%), Innovation (20%), Workforce (10%), and Costs (10%) [64]
Source: Adapted from Stuart and Forman

California's cumulative score puts it substantially ahead of other states. California's research capacity and openness to foreign students, level of potential venture capital funding (including that from foreign investors in countries that recent immigrants came from), and level of innovation account for most of its high ranking. Darby and Zucker's findings suggest that California may be able to jump-start its nanotechnology industry clusters with its in-place workforce training system.

Other parts of the nation, while not attracting as much venture capital as California, do have active nanotechnology investment. This is particularly true of Albany and Austin which have both attracted levels of capital to create facilities and jump start nanotechnology in their areas.[65] Lux Capital[66] notes that: "While total venture capital declined from 2001-2002, venture investments in nanotech increased (by 251% in electronics, 211% in industrial products, and by 313% in life sciences/nanobiotechnology). $900 million in venture capital has gone to nanotech companies since 1999, with $386 million invested in 2002."

64 Candace Stuart and David Forman (2003). The Final Numbers: Top Ten Small Tech's Hot Spots. Small Times, March/April.

65 Nova Workforce Board (2003). Nanotechnology: The Next Great Wave of Innovation. Nova workforce publications, publications@novaworks.org.

66 Mel Mendelson, Gary Kuleck, James Roe, Jeff Sanny, John Bulman, Rafiq Noorani (2003). Integration of the Basic Sciences and Engineering through Nanotechnology. International Conference on Engineering Education, July 21-25, 2003, Valencia, Spain.

Turning to the nano-workforce preparation score assigned to states by Stuart and Forman,[67] we find that California does not do as well. Citing work by Saxenian and Florida, they note that: "California offers a diverse and flexible work force largely populated with risk-tolerant, versatile and well-educated immigrants" but has a struggling K-12 education system that may not be able to keep up with workforce demands (see Figure 5.6).

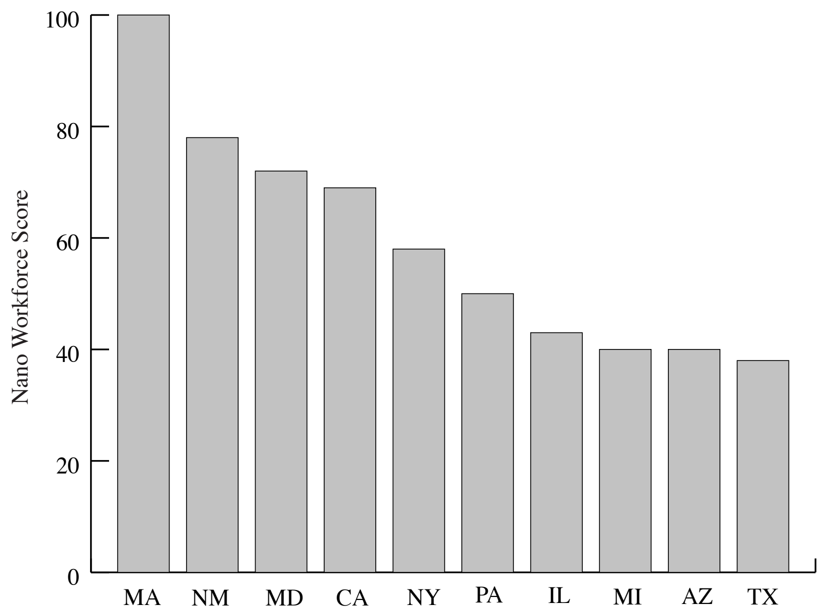

Figure 5.6: Ranking of Top Ten States by Nano Workforce Score (2003)
Source: Adapted from Stuart and Forman[68]

Variations in workforce training capacity among the states should be placed within the broader context of manufacturers' experience nationally with finding qualified workers for the technology oriented elements of their operations. For example, in 2003, 65% found it difficult to recruit qualified engineers, 47% with recruiting scientists and technical workers, 77% for craft workers, and 75% for technicians and electricians.[69] These findings suggest that no state is filling all of its manufacturing workforce needs and will be competing with other states and nations. These difficulties will probably be experienced by new nanotechnology based start-ups as they seek out even more specialized workers.

5.8 State Nanotechnology Initiatives

There is a wide variety of state nanotechnology initiatives. Some were created by state legislation (Oklahoma). Others are little more than declarations of purpose by a department or school in a university (Georgia Tech). Common elements include:

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[67] Candice Stuart (2003). Choosing the right ensemble: Top 10 states are those that can fashion the perfect small tech outfit. Small Times, March/April, p.38.

[68] Ibid.

[69] National Association of Manufacturers, Manufacturing Institute, and Deloitte and Touche (2003). Keeping America Competitive. Washington D.C.

- A recognition of the value of nanotechnology to the future economic prosperity of the region
- An awareness of the substantial federal investment in nanotech via the National Nanotechnology Initiative, and a desire to tap into this or related federal funding
- The private sector has been heavily involved in the initiative
- Initiatives tend to be very new – many date to 2003, and one was unveiled during the preparation of this paper (November 2003)

States rarely directly fund nanotechnology initiatives. Typically, states pass initiatives with an eye towards attracting grants and collaborations, but with few dollars committed up front. While workforce education is a component of most initiatives, there are few programs actively underway. However, there are three notable exceptions: New York (Albany region), Pennsylvania, and Texas.

New York's efforts center around the Albany Nanotech Center, at the State University of New York University at Albany. The state invested $28 million to begin the facility in 2000, and has attracted grants and private support to complete the $55 million facility. The center includes a School of Nanosciences and Nanoengineering, which has devised a curriculum and has participated in or hosted several education-related conferences and events.

> "The Center of Excellence in Nanoelectronics (CEN) is a fully-integrated technology deployment, product prototyping, manufacturing support, and workforce training resource for emerging generations of integrated circuitry (IC). Its targeted portfolio of nanoelectronics-based products ranges from emerging microprocessor and memory computer chips with higher functionality and complexity, to the rapidly evolving areas of micro- and nanosystem based "systems-on-a-chip" (SOC) technologies, including biochips, optoelectronics and photonics devices, and nanosensors for energy and the environment.
>
> The overarching goal of the CEN is to act as a world class center for pre-competitive and competitive technology deployment, quick turn-around prototyping, and workforce training and development using universal 200mm and 300mm wafer platforms. Its aim is to assemble the critical mass necessary for the creation of vertically and horizontally integrated industry-university consortia and public-private partnerships to convert long-term prospective innovations, as developed under the NORTH STAR and FC-NY, into real business opportunities…." [70]

Pennsylvania has a number of parallel efforts underway, several under the auspices of the Ben Franklin Technology Partners (BFTP). This economic development group, which operates out of four centers in Pennsylvania, secured $10.8 million in 2001 to develop associate degree programs in nanotechnology in southern Pennsylvania. The funding comes from a variety of sources including BFTP, Drexel University, the Pennsylvania Technology Investment Authority, and corporate donations. A BFTP organization founded in 2000, the Nanotechnology Institute (NTI), has also obtained a $600,000 grant from the Department of Education to develop a nanotech associate degree program in the Philadelphia area.

Pennsylvania is also home to the Pittsburgh Digital Greenhouse, a state-funded and industry-supported initiative designed to train people at the University of Pittsburgh, Pennsylvania State University, and Carnegie Mellon to become proficient in a specific microchip design industry ("System on a Chip"). While this is not a nanotechnology program per se, it has been cited as a

[70] http://www.albanynanotech.org/centers_programs/Nanotech.

possible model for nanotechnology training and education.

Texas has developed an initiative that focuses on education and training. Texas is seeking funding from the federal government for the initiative. A partnership between Rice University, the University of Texas, Austin, and the University of Texas, Dallas called SPRING (Strategic Partnership for Nanotechnology) is seeking "tens of millions" of dollars in federal and private grants. Another initiative centered at the University of Texas, Arlington called "Nano-at-the-Border" (N@B) is designed to develop both undergraduate curricula and partnerships with the K-12 community.

5.9 What Critical Time Limited Actions Are Necessary to Keep California's Nanotechnology Competitive Advantage?

There are a number of converging developments directly related to California's capacity to continue to develop and maintain its nanotechnology research and commercialization competitive advantage. These would appear to be:

- Over 50 countries are at an early stage in nanotechnology development. Japan and many European countries appear to be significant competitors given their investments in research and training. These activities seem to be smaller in scale than similar research activities in California but more advanced in terms of getting in position for workforce training. This also suggests that nanotechnology is a global industry cluster much like biotechnology with workers moving with their technical knowledge and creativity from region to region as industry segments develop and wages improve.
- There is a structural reorganization of manufacturing occurring in multiple industries emphasizing productivity as produced by a tighter tie between technological innovation, the information economy, and related workforce training. California is not losing manufacturing as quickly as the rest of the U.S. The state also has high technology clusters (biotechnology, materials, IT are examples) that enjoy considerable competitive advantage. However, a number of its industry sectors could be affected in as little as ten years by nanotechnology developments.
- California currently holds a competitive advantage over other U.S. states, particularly in research, innovation and venture capital. However, California is behind in workforce development, with several other states taking decisive actions to develop a nanotechnology workforce training capability. This problem is aggravated by California's changing demographics.
- California has a powerful nanotechnology research capability in three areas of the state potentially supported by strong venture capital, and workforce training structures. While the research sector is already far ahead in basic nanotechnology research, both venture capitalists and the workforce training sector have not yet responded. Venture capital must be available early on, and before it is for competing states and countries to permit first mover advantage. Workforce training must be tightly tied to university research and development in the private sector so that new curriculum can be developed "just-in-time' as new manufacturing processes come on line to produce new products.

California currently holds a competitive advantage over other U.S. states, particularly in research, innovation and venture capital. However, California is behind in workforce development.

In the face of this competitive reality, and considering that, if informed estimates are correct, substantial nanotechnology markets will begin to develop by 2007, significantly increasing by 2010, then:

- It is necessary to provide the kind of information that angel investors and venture capitalists need to distinguish "good risks" among nanotechnology start-ups.
- Basic research needs to continue to receive strong financial support so that federal and other monies and specialized nanotechnology institutes can be captured.
- Commercialization of basic research based nanotechnology process and products should be accelerated by supporting small start-ups.
- Higher education needs to establish a joint initiative to develop interlocking curricula for training scientists, engineers, and technicians. It may take up to two years to develop such curricula for four year and graduate schools, and six months to two years for the California Community Colleges including the Economic and Workforce Development Program.

5.10 What can California's research, workforce training, and related programs do to support the rapid emergence of nanotechnology industry clusters?

A number of federal and state government options are identified below that could help California establish and maintain its dynamic competitive advantage as nanotechnology emerges from university laboratories to simultaneously affect multiple industries and to establish new ones. The state should focus on the following goals:

5.10.1 Bring Federal Money to California

Much like it did for biotechnology, the California Delegation should unify to bring in research funds from the Nanotechnology Research and Development Act of 2003, which authorizes $3.68 billion over the next three years for nanotechnology research and development programs. Care should be taken that criteria are not established that award grants to states outside of a fair competitive process.

The Delegation could also support NSF's planned investment for Nanoscale Science and Engineering in FY 2005. The FY 2004 budget increased funding by $34 million to a total of $255 million, with five programmatic foci: 1) Fundamental Research and Education; 2) Grand Challenges; 3) Centers and Networks of Excellence; 4) Research Infrastructure; and 5) Societal and Educational Implications of Science and Technology Advances. The education and training activities will be extended to undergraduate and K-12 education.[71]

5.10.2 Develop Existing California Institutions

California is faced with a continuing budget crisis. Last year the University of California, California State University, and the California Community College System, including the Economic and Workforce Development Program, had their budgets very seriously reduced. K-12 education has also been seriously impacted. Additional budget cuts would reduce California's research, education, training, and start-up support capacity just when it is most needed to maintain nanotechnology competitive advantage. At a minimum, California must stay abreast of other states and nations by positioning its educational and training infrastructure to respond to nanotechnology's emerging needs. Fortunately, much can be done by realigning resources and by creating new interdepartmental and intra-educational relationships to produce new educational

[71] American Association for the Advancement of Science R&D Funding Update – NSF R&D in FY 2004 House-Senate Conference Appropriations, Dec 9, 2003, http://www.aaas.org/spp/rd/nsf04a.htm.

and training curriculum. The flow of new products and processes out of the laboratory is just beginning, suggesting that the initial investment need not be large but rather be strategic in the way existing resources are used.

Generally what is being suggested is creation of a virtual multi level education and training system that is paced to unfold as industry develops and venture capital is invested in various industry sectors. The suggested structure is "virtual" because it depends on rapidly networking and realigning existing resources across multiple K-12, higher education, and state agencies to respond in a "just-in-time" way. Options could include:

- Establishing a Nanotechnology Education and Workforce Advisory Council, with a charge to: track the development of the state's nanotechnology regional industry clusters; determine California's relative competitive advantage in critical sectors compared to other states and nations; use "red teams" drawn from participating state agencies staff to identify and recommend ways to address emerging nanotechnology educational and workforce training issues using state and other resources.
- Consider a range of actions to improve the flow of students, particularly women and underrepresented ethnic groups, into engineering and science-related careers. CCST and many other organizations have made a number of recommendations to improve science and engineering education and to link it to the community college, CSU, and UC systems. The Governor's Secretary for Education should review these recommendations and implement those that do not require additional funding.
- Take steps to enhance the workforce, such as:
    - Inventory Industry Driven Regional Collaboratives (IDRC) managed by the Economic Development Program, California Community Colleges Chancellor's Office projects linking business to college based workforce training to determine which lessons learned might be applicable to industry driven nanotechnology workforce training.
    - The Economic Development Program, California Community Colleges Chancellor's Office could establish a nanotechnology workforce training initiative. A portion of existing IDRC resources could be redirected in the normal funding process to begin development of a nanotechnology workforce training curriculum in each of the three nanotechnology regions. Industry and other higher education systems with significant nanotechnology research, or that have developed a nanotechnology undergraduate curriculum should be invited to participate. This curriculum should include modules that could be added on to existing training programs in biotechnology and related areas.
    - The Economic Development Program, California Community Colleges Chancellor's Office could establish a working collaboration with the California NanoSystems Institute to develop workforce training models, and modules, and to explore the possibility of developing two-year science degrees with an emphasis in nanotechnology. Pennsylvania's Nanotechnology Institute could serve as an example.
    - The California Labor and Workforce Development Agency could direct the Economic Strategy Panel, with the support of the Labor Market Information Division, to identify the components, workforce development and other needs of emerging regional California nanotechnology clusters.
    - The California Labor and Workforce Development Agency could direct the Labor Market Information Division, Employment Development Department, via budget language, to permanently assign an analyst to monitor the emergence of a nanotechnology industry cluster and related components in the three nanotechnology regions (Los Angeles, San Diego and the San Francisco Bay Area).

- The UC and CSU systems could consider introducing more nanotechnology and related science courses in existing engineering and new courses. Consideration could be given to adopting graduate and undergraduate nanotechnology curricula that have already been developed in other private colleges or states.
- The Workforce Investment Board, California Labor and Workforce Development Agency, could involve universities, business and the workforce in development and modification of a workforce training strategy for the industry.
- Request the Regional Technology Collaboratives in Los Angeles (Larta) and like institutions in San Diego, and San Francisco to form Nanotechnology Regional Interagency Working Groups to:
  - Align state, local, federal, industry, non-profits, and other sources with regional emerging industry needs in geographic areas.
  - Assist with providing venture capitalists and angels with obtaining appropriate information for vetting nanotechnology start-up companies for funding.
  - Consider forming a taskforce to address those elements of California's cost of doing business for small technology manufacturers that exceed those of other competitive states.

CHAPTER 6: SOCIAL AND ETHICAL IMPACTS OF NANOTECHNOLOGY

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Susan Hackwood
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Key Points in this Chapter:

In the next 5 to 10 years...

Nanotechnology will need much more research and substantial policy development

- Research on social implications lags significantly behind the scientific developments
- Nanotoxicology will emerge as a discipline to address the health, occupational, and environmental safety of nanomaterial manufacture and use
- Discrepancies and conflicts of jurisdiction between federal, state and agency law regarding nano product testing and regulation, intellectual property, and privacy issues will need to be sorted out
- Adequate mechanisms to objectively inform the public and policymakers about scientific, ethical, and economic implications of nanoscience and nanotechnology are lacking and must be developed

In the next 10 to 20 years...

Nanotech's impact will be impossible to ignore

- Regional evaluation centers, established in partnership with major nanotechnology research centers and industry clusters, will generate useful risk benefit analyses of nanomaterials and reviews of applicable regulations
- Genetic enhancement, "virus-like" nanostructures, military applications and the threat of terrorism are likely to create difficult ethical and safety issues – the policy infrastructure must be in place to handle these when they arise

6.1 Introduction

Nanotechnology has the potential to impact areas as diverse as materials and manufacturing; electronics, computation, and information technology; medicine and health care; biotechnology and agriculture; energy and the environment; aeronautics and transportation; chemical and pharmaceutical development and production; and national security. Significant social benefits are anticipated to emerge in each of these fields, in both the short and the long term, as a result of the investments in nanoscale research and development. With such a large and broad impact, however, it is reasonable to ask what the negative and undesirable consequences of this technological development may be, how we can anticipate them, and how we can minimize or eliminate their effects.

The social, ethical, and environmental implications of nanotechnology have been identified as an important topic of research and discussion. A general consensus, within both the scientific and policy communities, is that it is important to incorporate these issues into current work. The National Nanotechnology Initiative (NNI) designates as one of its five primary funding themes the societal implications of nanotechnology, including workforce education and training.[1] The

[1] Downey, M.L., ed. National Nanotechnology Initiative: The Initiative and Its Implementation Plan. NSTS/CT/NSET: Washington, D.C. 144. 2000.

National Nanotechnology Research and Development Program is furthermore tasked to "ensure that societal and ethical concerns, including environmental concerns and the potential implications of human performance enhancement and the possible development of nonhuman intelligence, will be addressed as the technology is developed." [2]

In the first workshops on the topic, both nanoscience researchers and social scientists agreed that an early focus on the social and ethical aspects was extremely valuable, based on three points. [3,4] First, the promise of nanotechnology to produce fundamental and widespread positive change across diverse fields has been heralded by many. A realistic assessment of the influence of this new technology, however, must include a recognition that negative consequences can also arise and often historically have not been adequately predicted. Account must be taken of both the potential benefits and the potential risks. Second, speculative fears of the consequences of advanced nanotechnology have influenced public perception. Many of these fears, such as plagues of self-replicating nanobots, are unjustified and inaccurate extrapolations, precluded by the laws of nature, of our current scientific understanding and technical implementation. But accurate and thoughtful concerns do exist, and to develop public trust and support and to engage the public in a discussion of desirable outcomes, such concerns must be examined early and openly. The lessons learned by the nuclear power and agricultural biotechnology industries have not been lost, and public concerns need to be addressed in an objective and forthcoming process to avoid unwarranted moratoriums on a potentially powerful and beneficial technology. Third, by involving social scientists, ethicists, and others in the research process from the outset, a unique opportunity exists to advance the understanding of the societal consequences of technology and to develop pragmatic practices for addressing them. Such cross-disciplinary assessment strategies are vital to enabling adaptive responses to new scientific and technological discoveries as they arise.

> Despite the allocation of funding resources, research on the social implications lags significantly behind the scientific developments.

One recent review of ethics research in nanotechnology, however, has concluded that despite the allocation of funding resources, research on the social implications lags significantly behind the scientific developments, even as the first nanomaterials products enter the marketplace.[5] In 2001, the NNI designated $16-28 million for social science research but spent less than half of that amount, as a result of an insufficient number of meritorious proposals. More tellingly, the number of nanoscience and technology publications and citations has steadily increased over the past ten years, but the number of nanotechnology-related social and ethical publications has remained negligible. A 2002 National Research Council review of the NNI recommended that the Nanoscale Science, Engineering, and Technology (NSET) subcommittee, which coordinates the NNI across agencies,

2 U.S. House. Nanotechnology Research and Development Act of 2003. 108th Cong., 1st sess., H.R. 766. http://www.house.gov/science/hearings/full03/may01/hr766.pdf .

3 Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

4 Roco, M.C. and Renzo Tomellini, R., eds. Nanotechnology: Revolutionary Opportunities & Societal Implications. Third Joint EC-NSF Workshop on Nanotechnology: Lecce, Italy, Jan. 31 - Feb. 1, 2002.

5 Mnyusiwalla, A., Daar, A.S., and Singer, P.A., "'Mind the gap': science and ethics in nanotechnology," Nanotechnology 14, R9-R13 (Feb. 2003).

"develop a new funding strategy to ensure that the societal implications of nanoscale science and technology become an integral and vital component of the NNI." [6]

This disparity is slowly being redressed, particularly with the establishment of two major centers focused on different societal aspects of nanotechnology: the NSF-funded Center for Biological and Environmental Nanotechnology (CBEN) at Rice University (specializing in the environmental and health effects), [7] and the program on the "Philosophical and Social Dimensions of Nanoscale Research" in the NanoCenter at the University of South Carolina (specializing in the public dialogue, nanotechnology stability and control, and visualization).[8] The latter program recently won a grant of $1.3 million from the NSF to support its studies. A second, similar grant was awarded to Lynne Zucker and her associates at UCLA for continued studies on the transfer of nanotechnology to the marketplace. Such awards demonstrate the potential that California universities have for capitalizing on their strong expertise in both nanoscale science and technology and social science, and for contributing to the development of research on the societal implications of nanotechnology. Additionally, the NanoBusiness Alliance, a nanotechnology trade organization based in New York, has announced the initiation of a Task Force on Health and Environmental Concerns, reflecting the nascent industry's concerns regarding safety. [9]

6.2 Goals in Responding to the Social and Ethical Implications of Nanotechnology

Two of the important results of the NSF workshops on societal implications were a description and categorization of the social, ethical, and environmental issues that might arise, and an identification of potential best practices and approaches for addressing these issues.[10] In developing a methodology for predicting and responding to rising social and ethical issues, two crucial points must be made.

First, nanotechnology is not a single monolithic pursuit, but rather an underlying convergence in scale among many different fields: physics, chemistry, biology, materials science, electrical engineering, and mechanical engineering. Discoveries in different subsets of these fields will enable radically different types of technological capabilities and applications. The production of new types of catalysts, for instance, will have a different range of societal effects than the implementation of semiconductor quantum dots.

Second, nanoscale science and technology, as a cohesive pursuit rising out of these scientific fields, is still a relatively young endeavor. It will be difficult to predict what the most important implications, benefits, and risks will be because many of the applications and their scientific underpinnings have yet to be understood. Even among the large number of potential technologies we can currently list, the exact uses to which the technology may be put are enormously diverse.

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6 Stupp, S.I., et al., Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative. 2002, National Academy Press: Washington, D.C.,2002.

7 Center for Biological and Environmental Nanotechnology (CBEN), Rice University, "Environmental/Health Effects of Nanomaterials" http://www.ruf.rice.edu/~cben/NanoEnviHealth.shtml.

8 University of South Carolina program on "Philosophical and Social Dimensions of Nanoscale Research" http: //www.cla.sc.edu/cpecs/nirt/index.html.

9 NanoBusiness Alliance, Task Force on Health and Environmental Concerns, 244 Madison Avenue, Suite 485, New York, NY 10016, http://www.nanobusiness.org/.

10 Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

Many of the studies and reviews of nanotechnology have classified projected developments into three categories: short term (3-5 years), medium term (5-15 years), and long term (greater than 20 years). The different time frames for different technologies to come to fruition should be taken into account in anticipating societal impacts, recognizing that the greatest capabilities are the farthest away and therefore the most uncertain.

Ensure California's Ability to Adapt to New Developments.

Because the potential far-reaching consequences of nanotechnology are so diverse, and because our understanding of what the possibilities and limitations are is still growing, it is essential to develop the capability and the structure for identifying, assessing, and responding to new social, ethical, and environmental issues as they arise out of emerging scientific and technical research. Such an analysis should be conducted on an ongoing basis, with a system in place to collect and act on new information. To adapt quickly in this manner would require the existence of a significant foundation of knowledge to draw from in nanoscience and technology, risk assessment, and the social science of technology.

Conduct Realistic Risk-Benefit Analyses.

An objective, inclusive assessment should begin with the identification and acknowledgement of the potential hazards that may arise from these nanotechnology-based alternatives. Studies can then be initiated on the nature of these hazards, evidence quantifying their impacts obtained, and solutions for minimizing harm while maintaining positive benefits determined. Such risk-benefit analyses must include the scientists and engineers responsible for creating new technologies, social scientists who understand the cascading effects of emerging technologies, and the public and their representatives who can define the desirable outcomes.

The suggestion, based on a strict precautionary principle, that a moratorium be applied to research in nanotechnology is both unrealistic and counterproductive. Nanoscience lies at the frontier of knowledge in multiple scientific fields; further progress in any of these fields implicitly involves imaging and control at the nanometer scale. Indeed, along many promising research avenues, it is simply not yet known what is possible, and a realistic assessment of the potential benefits and risks will only emerge with continued research. We are faced with many real and current problems in human and environmental well-being, and nanotechnology is expected to provide us some of the alternatives we need to solve these problems. The potentially significant benefits to the quality of human life must be included and balanced against the foreseeable risks.

Much of the discussion on the social and ethical implications of nanotechnology has centered on how to achieve these two capabilities, and a number of goals and practices have been suggested.

Develop a Core Base of Interdisciplinary Knowledge, Including Joint Work Between Nanoscientists and Social Scientists.

Studies of the social and ethical implications of nanotechnology should begin with a concerted effort to understand the science as it emerges. The best method for achieving this understanding is to incorporate social and economic research directly into the research structure from the earliest stages, enabling the establishment of partnerships and collaborations and the development of predictive measures and potential controls appropriate to the technology. One advantage of the support of social scientists through involvement in the scientific centers of research would be development of a specialized field, with social scientists who are cross-trained in some of the underlying science and technology. As Vicki Colvin, the Director of CBEN testified before the House Science Committee:[11]

> "Societal, ethical and environmental impact studies are also hard because they must envision a future technological reality. How can the social scientists and environmental engineers best equipped to complete this research choose which possible futuristic nanotechnology or nanomaterial to study? They could look to concrete data, such as the grand challenges of the NNI, to evaluate what specific technological goals have been articulated. Even better, they could partner with subject-matter experts early on. In this way they could study in real-time an evolving technology, and provide feedback to the researchers and students responsible for its development. For societal impact studies to be credible and effective, we must demand the active participation of nanotechnologists in the work. This would be best achieved by affiliating social scientists with major national nanotechnology centers, so as to provide investigators with a broad array of people and research to choose from."

Interest exists within the scientific community to initiate analyses of the broader implications of nanotechnology and to accept social responsibility for its discoveries and creation, but a strong forum or cohesive structure has yet to emerge, and California could play a role as a leader in this endeavor. Involvement can be encouraged by an organizational structure that supports ongoing conferences and seminars, publications, and other discussions. Individual nanotechnologists could also be involved by the effective incorporation of ethics training into the curriculum. The scientific professional societies and the major scientific centers and institutions can develop materials and programs focused on ethical issues specific to the nanotechnology fields and can provide resources for training nanoethics specialists who can contribute to the creation of these programs.

Conduct Specific Case Studies, Incorporating a Systems Approach, Life Cycle Analysis, and Real-Time Monitoring and Assessment.[12]

Rather than attempt to produce blanket statements, regulations, and limitations on broad categories of research and applications, emphasis should be placed on impact studies of specific technologies and applications. Such a focus is particularly useful in the assessment of the environmental and health effects of new materials and devices, where an examination of the full life cycle, from initial production to actual use to eventual degradation, produces maximum confidence in the ultimate impact. Concrete information on the technology and its practical contexts and settings enables cause and effect, and risks and benefits, to be more usefully identified. Solutions tailored to those particular cases can then be developed. Additionally, by modeling and monitoring in real-time any incremental changes due to environmental interactions, the response time to unexpected side-effects can be improved. These studies should be prioritized based on what technologies are expected to enter production earliest and on the degree of anticipated potential hazard.

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[11] Dr. Vicki L. Colvin, Director, Center for Biological and Environmental Nanotechnology (CBEN) and Associate Professor of Chemistry, Rice University, Houston, Texas. Testimony before the U.S. House of Representatives Committee on Science in regard to "Nanotechnology Research and Development Act of 2003," April 9, 2003. http://www.house.gov/science/hearings/full03/apr09/colvin.htm.

[12] Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

A more extensive systems approach would address the mutual interaction among research, technology and society, including an understanding of "how changes in one part of the system, whether a particular type of technology or a particular element of society, spread out to create intended and unintended effects throughout the system." [13] The applicable work by social scientists and historians is to develop theories that measure and explain social impacts and describe how differing mechanisms and circumstances will produce differing results, and thereby provide a basis for predicting alternative outcomes from the implementation of nanotechnology policies and guidelines.

Emphasize Objectivity, Neutrality, and Independence.

Openness and transparency in the procedures used to assess nanotechnology is vital. Risk-assessment must include the scientific and technical experts in the field but should also minimize the involvement of direct stake-holders, and mechanisms should be implemented to achieve a balanced analysis based on the available facts. The peer-review process inherent in the scientific establishment is an important element to insuring this objectivity. Additionally, acknowledgement should be made of those who may potentially be harmed in the implementation of new technologies and their concerns addressed.

Incorporate Prevention and Remedy into the Technological Development.

An explicit consideration of any potential catastrophic environmental and health consequences included in the development of new technologies, mechanisms for their prevention, and for the application of remedies should be in place in advance of production. An advantage of establishing social and ethical investigations early in the development of the technology is that solutions to potential harms can more easily be created before the technology matures and enters widespread use.

One proposed method for addressing the most severe of these concerns is to create a series of "trigger points" in laboratory results that would designate when greater social concern, oversight, and restriction is warranted. These trigger points would be "an accepted set of observations, which, if they begin to come true, represent a 'signal' to give attention to developments that may represent danger as agreed upon by prior considerations." [14] This list would be periodically reviewed to consider changes in nanoscale science and technology over time. Some examples of these conditions might include: the uncontrolled consumption of resources by a device or system; the potential for simple, inexpensive weaponization; and the development of computing machines that violate programmed predictability.

Identify and Analyze the Existing Legal and Operational Framework Applicable to Nanotechnology.

Regulations already exist, as do industry guidelines and procedures, to address technological concerns ranging from environmental impact and workplace safety to intellectual property. Many of these regulations may already cover nanotechnology applications, since nanotechnology itself has evolved out of existing fields and industries. For example, the workplace health and safety codes for the chemical production industry may already specify the requirements and procedures

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[13] Carroll, J.S., "Social Science Research Methods for Assessing Societal Implications of Nanotechnology," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 188-193.

[14] Tolles, W.M., "National Security Aspects of Nanotechnology," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 173-187.

needed to insure that widescale production of carbon nanotubes pose minimal health hazards to employees.

The jurisdiction and applicability of these laws to different emerging technologies need to be examined and specified, requiring the interaction of legal experts with nanotechnologists. "Nanostructured materials may pose serious practical and ethical challenges for particular policy domains, but these challenges will arise at a familiar macro scale, for which we have numerous rules, institutions and historical precedents. In contrast, nano-engineered mechanisms will force us to reformulate our rules and institutions to govern an unfamiliar setting with which we have no prior experience." [15] Again, there is an opportunity to leverage the existing expertise in California to address these issues.

Establish a Dialogue with the Public and Policymakers.

Public education, involvement, acceptance, and choice are essential in defining the future of nanoscale research and development. One very important goal, therefore, is to establish a venue for the exchange of ideas between the scientific community and the general public. This exchange includes educating the public about nanoscience, its realistic and probable outcomes and limitations, and its practical impacts. In doing so, unwarranted fears and concerns can be replaced with an informed consideration of, and ultimately oversight over, the desired direction of nanotechnology applications. Creating a centralized, reliable source of information regarding nanotechnology may be particularly useful for interacting with the news media, providing access to accurate information, and encouraging dialogue and outreach.

The dialogue should also include feedback from the public regarding the social and ethical issues to help guide the priorities in applications research and the criteria and procedures for decision-making. One goal should be to collate the public response to enable accessibility and to encourage continued openness of those working in nanotechnology to public input. Scientists should additionally be connected to the end users of potential technology – for instance in the medical, manufacturing, or environmental engineering communities – to understand what practical issues will arise through the use of that technology.

One mechanism suggested to accomplish these goals is the creation of citizen/scientist panels that would enable the full range of different opinions and viewpoints on the consequences of nanotechnology to be elicited and discussed. [16] By engaging in these working relationships and emphasizing openness, a foundation of trust can also be established between the public and the experts in various nanotechnologies. A working model for a citizen advisory panel is the North Carolina Citizens Technology Forum, "a National Science Foundation project to implement both a face-to-face and Internet-based citizens' consensus conference on technology policy," that previously produced a report on genetically modified foods.[17]

Measures of public acceptance of, resistance to, or rejection of nanotechnology in each of its various subfields could also be developed, clarifying where the primary public concerns and

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[15] Suchman, M.C., "Envisioning Life on the Nano-frontier," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 211-216.

[16] Weil, V., "Ethical Issues in Nanotechnology," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 193-198.

[17] The North Carolina Citizens Technology Forum, National Science Foundation project, Macoubrie, J., co-principal investigator, http://www.ncsu.edu/chass/communication/ciss/sponsored.html.

interests lie. Some of these could be found in surveys of public attitudes, others in an observation of the economic trends and changing labor markets.

Additional areas for investigation include research on the underlying economic and non-economic reasons for acceptance or rejection of new technologies, the impact of market drivers on the development of nanotechnology, and methods to convey highly technical information to the public in an accessible manner.

6.3 Establishment of Nanotechnology Assessment (Nanoethics) Centers

The creation of one or more nanoethics centers is one attractive means for achieving a successful assessment of nanotechnology's social and ethical implications.[18] These centers would act to generate a cohesive focus on the relevant issues, incorporating and following the methods listed above. Formed from the existing base of knowledge and expertise in the state, they would attract nanoscientists and social scientists and provide them with the resources and infrastructure to conduct ongoing studies of nanotechnology's effect on society, to develop means of and recommendations for addressing these effects, and to act as a conduit among the scientific community, the media, the public, and policymakers. In addition to preparing studies on the impacts of nanotechnology and developing ethical guidelines and best practices for its safe and beneficial use, they would be designed to provide centralized access to an extensive base of knowledge, a continuing awareness of developments, and an ability to flexibly advise and act on an appropriate time scale.

The Center for Biological and Environmental Nanotechnology (CBEN) at Rice University is one major center funded by the NSF as one of its six Nanoscale Science and Engineering Centers. Similar to researchers there, California researchers could generate some of the first specific, scientific risk-assessment studies on the impact of particular nanotechnologies. The Center for Science, Technology, and Society at Santa Clara University is an example of one California-based university center set up to address technology's social and cultural impact, in this case information technology.[19] Current NSF budgets for nanotechnology include funds for the Societal and Educational Implications of Science and Technology Advances, with $9.28 million requested for FY 2003, approximately 4% of the total NSF investment in nanoscience and technology. California universities with strong nanotechnology research efforts should be encouraged to establish centers on societal impacts and should be positioned to apply for these grants, and California social science researchers should be encouraged to develop connections with the leading nanotechnology researchers. The opportunity and value of doing so is particularly large considering these funds have not been fully utilized for lack of sufficiently strong proposals.

> **California universities with strong nanotechnology research efforts should be encouraged to establish centers on societal impacts.**

The Nanotechnology Research and Development Act, passed earlier this year includes a requirement for a study "to assess the needs for standards, guidelines, or strategies for ensuring the development of safe nanotechnology," to be conducted within six years.[20] By creating a structure to encourage the

[18] Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

[19] Santa Clara University, Center of Science, Technology, and Society http://sts.scu.edu/.

[20] U.S. House. Nanotechnology Research and Development Act of 2003. 108th Cong., 1st sess., H.R. 766. http://www.house.gov/science/hearings/full03/may01/hr766.pdf.

study of these issues and thereby support the development of expertise among university faculty, California would be able to contribute significantly to that national report.

The nanotechnology private sector, including industry-wide consortia, could act as an additional source of knowledge and seed money for the study of social implications, including forming partnerships with academics, allowing access to research, and providing feedback. The NanoBusiness Alliance's Task Force on Health and Environmental Concerns provides evidence for industry interest in these issues; an analogous California group is the Northern California Nanotechnology Initiative (NCnano), which aims to unite "the extensive research, development, manufacturing, and capital resources of Northern California to create the world's leading nanotechnology cluster." [21]

Much of the discussion on the social and ethical implications of nanotechnology has focused on the best ways to assess and respond to the evolving implications of nanotechnology. Considerable attention has also been paid, however, to what the major issues are currently foreseen, and the remainder of this chapter summarizes the primary categories of concern.

6.4 Environmental and Health Risks (Nanotoxicology)

The impact of nanotechnology on the environment and on the associated dangers to human health is one of the most important issues that needs to be studied. The commercial synthesis of functional materials with nanometer dimensions has already begun, and little data exists on the impact large quantities of these new materials will have on the environment. The nanotechnology business community is aware of these concerns; F. Mark Modzelewski, the executive director of the NanoBusiness Alliance testified, "Another grave fear that is often expressed by CEOs, particularly at large corporations that are undertaking nanotech R&D, is uneasiness over the lack of research on nanotech health and safety issues. More than one CEO has asked "are we sitting on the next asbestos working with all these tiny things?" [22] Wider public concern has begun to emerge as well, reflected in the publication of such reports as "Future Technologies, Today's Choices" for the Greenpeace Environmental Trust. [23]

Specific research on the environmental and human health effects of nanotechnology is only now being conducted, with preliminary data available in a few studies on nanoparticle toxicity.[24, 25] These early studies suggest that single-walled carbon nanotubes and nanoparticulates of the polymer polytetrafluoroehylene can, after direct instillation onto the tracheas of rats, cause inflammation of lung tissue and formation of microscopic lesions. It is unclear, however, whether these particulates ultimately have any toxicity, especially in comparison to ultrafine particulates already found in ambient pollution, and even whether these materials will form structures that are actually

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[21] Northern California Nanotechnology Initiative http://www.ncnano.org/.

[22] F. Mark Modzelewski, Executive Director, NanoBusiness Alliance. Testimony before the U.S. Senate Subcommittee on Science, Technology, and Space Subcommittee, Hearing on Nanotechnology, Sept. 17th, 2002.

[23] Arnall, A.H., "Future Technologies, Today's Choices: Nanotechnology, Artificial Intelligence and Robotics; A technical, political and institutional map of emerging technologies," Greenpeace Environmental Trust: London, England, July 2003. http://www.greenpeace.org.uk/MultimediaFiles/Live/FullReport/5886.pdf.

[24] Dagani R., "American Chemical Society National Meeting – Nanomaterials: Safe or Unsafe?" Chemical & Engineering News 81 (17), 30-33, April 28, 2003. http://pubs.acs.org/isubscribe/journals/cen/81/i17/html/8117sci2.html.

[25] Service, R.F., "News Focus – Nanomaterials Show Signs of Toxicity," Science 300, 243 (April 11, 2003). http://www.sciencemag.org/cgi/reprint/300/5617/243a.pdf.

respirable when inhaled in a natural environment. Further studies to answer these questions are in progress. Additionally, it is unknown to what degree different nanometer scale materials may be able to enter the body through skin exposure.

In general, nanotechnology is likely to produce a wide range of materials of vastly different structures and natures, and there are currently few data on which, if any, of these may have damaging effects. Nanostructures designed for use in medicine and in drug delivery are already demonstrating to be completely benign as well as useful. It is possible, on the other hand, that some nanoscale materials may, as a result of their small size as well as their chemical composition, have some physiological toxicity.[26] Additionally, it has been postulated that, while innately harmless, some materials when released into the environment may act as carriers capable of transporting other chemicals through cellular barriers or may enter and accumulate in the food chain. Since nanotechnology heralds the creation of new catalysts, some of which may function increasingly like natural enzymes, the effects of these catalysts on the environment should be considered to insure that they are safer and better than what we currently have.

It is the transition to large-scale commercial manufacturing of these materials that is the primary concern, not the small amounts of material produced in the research process. The exposure of workers to nanoparticulates will require investigation, and potential regulation as with chemicals found to be hazardous but useful. With large production quantities, it will also be important to study the full life-cycle of these materials, including the associated process of producing them, their use, and eventual disposal. Nano-composites, for example, may be more difficult and more energy-intensive to recycle than single-phase material, and may accumulate in the environment over time. Since environmental impacts may be slow to develop and ascertain, one of the challenges will be to determine what needs to be monitored over the course of time as an important and relevant effect.

Eventually, the legal and regulatory structures currently in place will need to be reassessed in the context of the broad range of nanotechnologies. The Toxic Substances Control Act and the Food, Drug, and Cosmetic Act already require government review and certification of new chemicals before they can be produced and sold. Will they need to be modified to account for toxicity that results from size rather than from chemical composition alone? What role will different regulatory agencies have to play?

A secondary regulatory issue may arise as new nanoscale analytical methods enable the detection of chemicals toward the limit of single molecules. The ultrasensitive detection of trace amounts of known hazardous materials will require health risk thresholds to be clearly defined and defended based on scientifically accurate toxicity data.

Even with these environmental concerns, however, it is important to recognize that many of the new nanotechnologies will not have direct environmental impacts. Furthermore, nanotechnology holds the promise of producing great strides in sustainable development and environmental preservation. For California to remain at the forefront of issues in energy and the environment, health, and safety, we need to take advantage of the beneficial capabilities of nanotechnology while maintaining an awareness of any damaging side-effects. In the words of Edward Tenner, "If we freeze technology, we perpetuate and amplify the environmental and social costs of the status quo, including the degradation of air and water quality and the acceleration of climate change. We are

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[26] Masciangioli, T. and Zhang, W-X., "Environmental Technologies at the Nanoscale," Environmental Science and Technology, March 1, 2003. http://www.nano.gov/GC_ENV_PaperZhang_03-0304.pdf.

on a technological treadmill. We have to find new ways to do things, and nanotechnology can not be excluded." [27]

Nanotechnology promises a significant reduction in the consumption of natural resources, energy, and water, and in the associated environmental discharges, needed to produce products for a given task, in arenas ranging from transportation to lighting and computing. The use of strong yet light-weight material based on nanotechnology in vehicles could save up to 15 billion liters of gasoline over the life of one year's production of vehicles in the United States.[28] Other anticipated benefits are the improved remediation of waste and pollution, including new techniques for desalinization and for purification of waste water, and increased efficiency in energy production, including solar energy generation and eventually the production of other alternatives to fossil fuels. Some of the specific research on environmentally beneficial applications is discussed in a 2002 workshop report by the Environmental Protection Agency (EPA),[29] and an excellent summary was recently written on the environmental benefits as well as hazards of nanotechnology.[30]

6.5 Self-replication and Nanobots

One of the first fears to arise concerning the negative unintended consequences of nanotechnology was the potential devastation resulting from the uncontrolled self-replication of nanoscale devices (or "nanobots"). This potentiality has been determined by the nanoscience community to be unrealistic, based on the fundamental physics and chemistry involved and on the limitations on our ability to implement the high degrees of complexity necessary to produce such structures in the foreseeable future. This conclusion was described in the report, "Social Implications of Nanoscience and Nanotechnology," as well as by a number of others.[31, 32, 33, 34, 35]

> One of the first fears was the potential devastation resulting from the uncontrolled self-replication of nanoscale devices (or "nanobots"). This potentiality has been determined by the nanoscience community to be unrealistic.

[27] Tenner, E., "Nanotechnology and Unintended Consequences", Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 241-46.

[28] Garcés, J.M. and Cornell, M.C., "Impact of Nanotechnology on the Chemical and Automotive Industries," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 55-59.

[29] Karn, B. and Savage, N., EPA Nanotechnology and the Environment: Applications and Implications STAR Progress Review Workshop, The Office of Research and Development's National Center for Environmental Research: Arlington, Virginia, August 2002. http://www.nano.gov/GC_ENV_EPA2002_Proc_03-0204.pdf.

[30] Masciangioli, T. and Zhang, W-X., "Environmental Technologies at the Nanoscale," Environmental Science and Technology, March 1, 2003. http://www.nano.gov/GC_ENV_PaperZhang_03-0304.pdf.

[31] Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

[32] Tolles, W.M., "National Security Aspects of Nanotechnology," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 173-187.

[33] R. E. Smalley, "Of Chemistry, Love, and Nanobots", Scientific American, Sept. 2001, p. 76-77.

[34] G. Stix, "Trends in Nanotechnology: Waiting for Breakthroughs," Scientific American, April 1996, p. 94-99.

[35] Quoted in: Service, R.F., "Is Nanotechnology Dangerous?" Science 290, 1526 (2000).

A so-called "molecular assembler" capable of building copies of itself from the resources available in the environment would require three key abilities: spatial mobility, recognition of its chemically complex surroundings, and the manipulation of individual atoms to act as nutrients and as the building blocks for self-replication. The simplest known form of life capable of self-replication is a virus, and a virus requires the chemical machinery of another living organism for the nutrients and conditions it needs to reproduce. A nanodevice capable of replication from an arbitrary environment would have to be enormously more complex than a virus, and is therefore conceptually beyond what we can currently envision. The chemistry of interactions between atoms suggests that the ability to mechanically assemble complex, arbitrary structures atom-by-atom is implausible.

It is important to clarify that the term "self-assembly" often used in nanoscience has a very specific scientific meaning that is quite different from the term "self-replication." Self-assembly refers to the ability to prepare systems such that the natural physics and chemistry dictate the assembly atoms and molecules to produce very particular structures with nanoscale dimensions. It is analogous to the process by which snowflakes form to produce complex structures, under the right conditions and without the ability to self-replicate.[36] The process of self-assembly plays a fundamental role in developing "bottom-up" processes for converting and placing nanoscopic structures into more functional and complex systems.

NANOSCIENCE AND NANOTECHNOLOGY ARE LIKELY TO REMAIN A CORE COMPONENT OF DEFENSE R&D FOR MANY YEARS TO COME.

The conclusion is that any self-replicating organisms to emerge will be biologically based and strictly analogous to viruses. The emergence of new viruses, however, represents a significant threat, with realistic potential to trigger large-scale plagues. The development of genetically engineered viruses should therefore be handled with extreme care and under strict guidelines, though it should be noted that genetic manipulation of viruses may enable the production of vaccines. The development of nanotechnology used to assist in genetic manipulation will then fall under those existing guidelines.

6.6 Security and Terrorism

As with any new and diverse technology, nanotechnology provides many potential applications for enhancing military capabilities. These positive enhancements fall into numerous categories, including: better weapon platform and system performance and longevity resulting from advanced nano-materials; increased information communication, handling, and analysis capacity (including quantum cryptography); remote miniature sensor system capability with high mobility, sensitivity, and selectivity (including for nuclear, chemical, and biological threats); and improved physiological monitoring and casualty treatment of military personnel through medical advances.[37] With such a wide range of military applications, nanoscience and nanotechnology are likely to remain a core component of defense R&D for many years to come.

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[36] Theis, T.N., "Information Technology Based on a Mature Nanotechnology: Some Societal Implications," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 60-68.

[37] Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

New offensive and defensive capabilities will be available to all who have acquired the technical knowledge and manufacturing infrastructure. It is prudent, therefore, to assess and anticipate the threats that nanotechnology-based weapons present, to develop appropriate countermeasures, and to continue to reassess those threats as new applications emerge. The weaponization of nano-materials or nano-devices would be of considerable concern if they can generate a significant threat with minimal difficulty in construction.

Concerns that rogue states, terrorist groups, or individuals could produce and endanger others with "smart" self-replicating miniature robotic systems are not supported by the technical feasibility of such devices. The small size of materials and devices produced by nanotechnology, however, do provide two realistic security challenges. First, such materials or devices could be very difficult to detect and therefore to provide barriers against, whether as harmful agents or as intelligence-gathering devices. Second, nanotechnology may provide a means of enhancing the delivery and controlled targeting of biological and nerve agents, with nanoscale artifacts acting as carriers. [38] Here, the expertise developed in addressing biotechnology related security concerns as related to biological warfare could provide guidance.

Conversely, nanotechnology may itself provide a means for highly sensitive detection of such threats. The detection of biological and chemical weapons is expected to improve through the use of arrays of sensors tailored on the nanoscale, and the improved remediation of contaminated areas and structures is also anticipated.

Recognizing that discovery and innovation require openness and free exchange of ideas to flourish and that distinguishing beneficial civilian applications of technology from military ones is often difficult, the determination of any specific and limited cases in which it will be appropriate to place strict controls on nanotechnology-related information will present a challenge, including a challenge to California's national laboratories.

6.7 Economic Displacement, Equity, and Ownership

Economists and social scientists have the task of anticipating the effects of nanotechnology as it ripples through the economy, from the initial changes in the improvement of industries to the shifting demands and expectations of consumers to the eventual large shifts in infrastructure, workforce, and society they may produce. Since nanotechnology has the potential for changing the means of production across multiple industries, this social impact may be dramatic.

Among the major shifts will be the technical training and background necessary to support the new technology – its production, its implementation, and its further research and development. Changes in industrial production will translate to new avenues of economic growth and personal opportunity. But as new processes and industries replace older ones, there will inevitably be a displacement of workers, and the turmoil of this industrial transition can be mitigated by an awareness of and readiness for the socioeconomic changes. As the speed of technological change increases and as specialized understanding of processes at the small scale and the tools necessary to access them becomes more prevalent, we can expect an increase in the needs for a workforce trained in science and technology. Education will therefore be a key factor to participating in the economy, and these issues are discussed in extensive detail in chapter 5.

[38] ESANT, "Economic and Social Aspects of Nanotechnology," Report of working group 6 of the Euroconferences on Nanoscience for Nanotechnology: Antwerpen, Nov. 21-24, 1999. http://www.nano.org.uk/ESANT99.htm.

The effect of nanotechnology on the divide between rich and poor – on the accessibility and equity of technological and economic benefits – is another primary issue, and it is yet unclear what that effect will be, with the technology perhaps increasing the divide in some industries and reducing it in others. What will be the ultimate cost and availability of nanotechnology-driven improvements in health care and information technology? How will the balance between increased performance and lower cost play out? As manufacturing processes utilize a new set of materials to achieve desired properties, scarce resources once high in demand may decrease in value. Long-term developments in nanotechnology may enable increases in agricultural productivity at minimal cost. Who will benefit the most? Even the costs of the facilities to fabricate new nano-materials and nano-devices are uncertain. To mass-produce these products may require an enormous initial capital expense, prohibiting all but a few large companies from controlling that production. Conversely, new catalysts and new self-assembly routes to production may reduce the size and scale of facilities necessary.

Finally, new legal issues in intellectual property and private ownership will arise. The novel features of nanotechnologies are likely to create new complexities in intellectual property protection that accelerate the debates currently underway, including over how the control of patents for primary fabrication techniques affects innovation and what the role of universities should be in creating new companies. As the distinction between chemical molecules and small-scale devices blurs, the issue of ownership of individual molecules may arise. Similarly, if small-scale devices can infiltrate and occupy small spaces in the ambient atmosphere, in the human body, or elsewhere, should they be owned by the original producer or purchaser of the device, or by the owner of the space in which they exist? And who is legally responsible for preventing the infiltration of these devices into private property?

6.8 Privacy

The potential availability of devices that can sense and act on the small scale and that can broadcast information to a communication network raises a number of issues related to privacy. Two aspects of nanotechnology provide the basis for these concerns. The first is its application to information technology, improving the ability of computation systems to communicate, store, and manipulate very large sets of data. The second is its application to sensors, and the production of virtually invisible sensing devices with widespread distribution. Micro electro mechanical systems (MEMS)-based sensors designed to accumulate useful information on its local environment – chemical content, temperature, visual images, etc. – could be placed almost anywhere. DNA sensors could likewise provide vital medical information on patients.[39] But with improved mobility, these sensors could gain access to private locations, including the human body itself, and avoid detection, although no such technology as yet exists.

A preview of some of the issues raised by pervasive sensing and computing can be found in the current debate over the use of radio frequency identification (RFID) by manufacturers and retailers to keep track of their inventory. By embedding small chips into their products, information can be stored and accessed by use of a RFID reader, with the distance at which these RFID tags can be read limited to less than ten feet for chips without an embedded power source.[40] The businesses investigating this technology are primarily interested in improved cost-effectiveness

[39] Smith, R.H., "Social, Ethical, and Legal Implications of Nanotechnology," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 203-211.

[40] RFID Journal, Frequently Asked Questions. http://www.rfidjournal.com/article/articleview/207.

in internal logistics, but there has been public concern over the fate of these tags after they are sold to the consumer. Nanotechnology will impact pervasive computing through the increasing miniaturization of sensor chips and ID tags. In this context, however, it will not introduce fundamentally new abilities, simply an evolution and extension of current technologies.

The primary question, then, is how to set guidelines for the collection and use of information when it becomes possible to acquire and manipulate very large sets of data, and thereby to track and predict patterns of behavior. [41] There are many cases in which commonplace sensing devices could be very beneficial – in the detection of hazardous substances, for instance. Recognizing that there is commercial advantage to accumulating information, how should the information business and individuals have a right to be defined and regulated? Will fair-use clauses requiring notification on products incorporating sensors be necessary and appropriate? Will the detection of unauthorized sensors in itself require the widespread placement of sensors? These questions will likely have to be addressed on a case-by-case basis as new applications of nanotechnology emerge.

6.9 Other Issues

6.9.1 Medical Technology

Much of nanotechnology's most profound potential for the improvement of the quality of life is in the area of medical technology. A significant number of medical and health care advances are likely to result from current developments in the field, and they provide some of the most compelling arguments for supporting the progress of nanoscience. Detection, diagnosis, and treatment at the cellular level may become possible through an increased understanding of the molecular basis for biological interactions and of methods for designing and synthesizing structures that take advantage of them. New diagnostics and sensors will enable probing of genetic predispositions, recognition of the first early signals of disease, and monitoring of local cellular conditions, as well as communication of that in vivo information to the exterior world. Drug encapsulation and molecular recognition techniques will allow the targeted delivery of drugs to damaged cells or tissue, and microelectromechanical devices incorporating sensors and refined delivery systems may act as "implantable pharmacies," applying treatments when necessary. Biomolecular motors running off the chemical energy of the human body may be utilized as power sources for implanted devices, and new biocompatible coatings and materials may enable significant advances in wound healing and tissue repair or replacement with artificial components.

> Much of nanotechnology's most profound potential for the improvement of the quality of life is in the area of medical technology.

With such potential, and in many cases as a result of exactly the desired improvements in medical capabilities, a number of ethical issues arise. The largest of these involves medical diagnostic information. If sensors that monitor internal conditions can broadcast their information, controls may need to be implemented to protect the privacy of the patient. With ultrasensitive detection of the earliest stages of diseases and conditions, and with availability of genetic tests and predictors

[41] Whitesides, G.M. and Love, J.C., "Implications of Nanoscience for Knowledge and Understanding," Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001, pp. 104-116.

of medical predispositions, the appropriate access to and use of that information by insurance providers would also have to be determined.

The size scale and biological activity of new pharmaceuticals and devices will need to be taken into account in ascertaining the safety of new treatments, especially regarding the implications of failure in implanted devices with active components such as drug delivery. Any future devices that incorporate genetic materials or act to repair or modify genetic structure must be carefully scrutinized.

Finally, as nanotechnology plays a role in improving health care, the costs and equitable distribution of medical treatments will continue to be an important issue, especially as technology helps to extend lifespan.

6.9.2 Cultural, Moral, and Philosophical Aspects of Nanotechnology

As nanotechnology develops, it will contribute to breakthroughs across fields, and combined with biotechnology and information technology, it is expected to increase the rate of technological change. As this change comes more and more rapidly, people will be required to adapt with increasing rapidity to the ripples technology sends through the social and economic structures. The advance of technology must be balanced against the ability of social institutions, conventions, and morals to provide continuity and context for human life. The discomfort many feel about the speed of technological advance is a reflection of the inherent desire for stability and predictability, even in the quest for improved control over nature.

Nanotechnology will also begin to blur the boundary between the physical and life sciences, improving our ability to interact with nature at the cellular level. It will redefine what we consider to be machines, and what capabilities those machines will have. And in so doing it my change our perception of what is "natural" and what is "artificial," and generate continued philosophical discussion on the interaction between technology and human nature.

6.10 Summary and Conclusions

Nanotechnology has great potential for producing important advances of social and economic value. It spans a wide variety of scientific disciplines and commercial applications, and therefore involves an equivalent diversity of social, ethical and environmental issues. In considering how to take advantage of nanotechnology's benefits while maintaining a reasoned approach to managing its risks, a few primary conclusions can be drawn:

- The diversity and continuing evolution of nanotechnology requires the ability to respond flexibly and adaptively to emerging social, ethical, and environmental issues by forming a core foundation of interdisciplinary knowledge.
- A series of best practices and approaches to nanotechnology suggests the formation of centers, focused on utilizing technical knowledge to anticipate problems and develop solutions.
- California is well placed to take advantage of centers for nanotechnology social and ethical issues, based on the research strengths in the state.
- Fears of catastrophic self-replication of nanoscale machines are unwarranted.
- Health and environmental concerns, particularly nanoparticle toxicity, are realistic and deserve to be studied further.

CHAPTER 7: PLANNING FOR CALIFORNIA'S FUTURE IN NANOTECHNOLOGY: RECOMMENDATIONS

Key Points in this Chapter:

Options recommended for California's policy makers:

- *For the California Congressional Delegation:* Support implementation of the Boehlert-Honda Nanotechnology Act and the 21st Century Nanotechnology Research and Development Act
- *For the California Legislature's Joint Committee on Preparing California for the 21st Century:* Create a Select Committee on New and Emerging Technologies in each house of the Legislature, charged with identifying emerging technology issues, monitoring federal programs affecting the state, and addressing intellectual property, ethics, and public education issues
- *For the Governor's Office:* Establish a Nanotechnology Research and Workforce Advisory Council staffed by the Governor's Office of Planning and Research to monitor California's competitive advantage, create forums, and recommend policy actions
- *For the Governor's Secretary of Education:* Create a K-12 Science and Engineering Initiative including nanotechnology
- *For the Governor's Office of Planning and Research:* Recommend changes in tax incentives and local land zoning to foster manufacturing spin-off locations within the state of California
- *For the California Community College, State College and University Systems:* Create a research and technician workforce training plan for California and implement appropriate curricula and major options to support nanotechnology training
- *For California State Government Agencies and Departments:* Additional recommendations are offered for the health and environmental protection related agencies, the Labor and Workforce Development Agency and the Business, Transportation and Housing Agency

This chapter gives a more detailed set of recommendations that have emerged as a consequence of analyzing the information presented in the previous six chapters.

7.1 When must California's government act?

The global race to establish competitive advantage is on with many states and nations seeking to knock California from its leading research role and to move more quickly than the state is to commercialize research results. Many have developed a flexible strategy that networks key components of the emerging nanotechnology industry cluster together in way that leverages resources without restricting creativity or entrepreneurship. California lags behind this effort and has not developed a similar strategy to leverage its considerable resources and current competitive advantage. There are a number of converging future developments directly related to California's capacity to continue to develop and maintain its nanotechnology research and commercialization position. Policy decisions must be made now to deal with these developments and to preserve California's current competitive advantage. These converging developments would appear to be:

- Over 50 countries are at an early stage in nanotechnology development. Japan and several European countries appear to be significant competitors given their investments in research and training. These activities seem to be smaller in scale than similar research activities in California but more advanced by perhaps two years in terms of developing a

It may be difficult for California to catch up with the rest of the nation and the world if it cannot increase the number of underrepresented groups in California's nanotechnology research and technician training programs over the next few years.

coordinated strategy for research and technician workforce training. This also suggests that nanotechnology is a global industry cluster much like biotechnology with workers moving with their technical knowledge and creativity from region to region as industry segments develop and wages improve. The advantage of one region cannot be long maintained under such conditions. California may benefit in the short run from migration from other countries' and states' technician training programs if the state can maintain its quality of life and high wages. California may also be able to continue to attract talented immigrants to its colleges and universities from other nations.

- It may be difficult for California to catch up with the rest of the nation and the world if it cannot increase the number of California's underrepresented groups in nanotechnology research and technician training programs over the next few years. These high school through graduate school programs are also behind by at least two years in establishing and implementing an integrated, strategic workforce development training program. This problem is aggravated by California's changing demographics.
- There is a global structural reorganization of manufacturing occurring in multiple industries emphasizing productivity. Here competitive advantage is produced by a tighter tie between technological innovation, the information economy, and related workforce training. California is not losing manufacturing as quickly as the rest of the U.S. The state also has high technology clusters (biotechnology, materials, IT) that enjoy considerable competitive advantage. However, a number of its industry sectors could be affected in as little as five to ten years by nanotechnology developments that must also include such productivity advantages.

California currently holds a competitive advantage over other states, particularly in research, innovation and commercialization of nanotechnology.

- California currently holds a competitive advantage over other states, particularly in research, innovation and commercialization of nanotechnology. Early-stage investment in established high technology sectors leads the other states by at least six months. This advantage must be transferred to nanotechnology start-ups.
- The handling of intellectual property (IP) is a growing issue. The nature of new IP in nanotechnology is continually redefined. Questions such as whether atoms can be patented are just now being asked. There are also many inefficiencies that affect the transfer or sharing of IP between universities and state agencies and industry. These issues must be addressed as California moves forward.

In the face of this competitive reality, and considering that, if informed estimates are correct, substantial nanotechnology markets will begin to develop by 2007, significantly increasing by 2010, then the following general strategy may be appropriate:

- Basic research must continue to receive strong financial support so that federal and other monies and specialized nanotechnology institutes can be captured and our long term basic research advantage preserved.
- The three to four year commercialization of basic research based nanotechnology processes and products should be accelerated by supporting small start-ups with the trained workers and business management skills.
- It is necessary to immediately provide information that angel investors and venture capitalists need to quickly distinguish "good risks" among nanotechnology start-ups as they emerge.
- California's higher education institutions could immediately establish a joint initiative to develop interlocking curricula for training scientists, engineers, and technicians. Other states' and nations' efforts can serve as a model. It may take up to two years to develop such an integrated curricula for four year and graduate schools, and six months to two years for the California Community College's Economic and Workforce Development Program. The effort should extend down to the high schools as well.
- A political and economic mechanism for studying and preventing potential problems involving the new technology could be quickly developed. New political mechanisms are needed to identify new, high risk technology applications. Improved means of modeling the environment and monitoring incremental changes caused by unexpected (or expected) side-effects of the new technology could be used to incrementally move developments forward. This information should be made public.

In the next section, we provide recommendations drawn from the research in the first six chapters of this report, each of which analyzes a different aspect of nanotechnology and its implications for California. They provide a guideline for what needs to be done in order to ensure California maintains technological, economic, and social leadership in nanotechnology. There are many steps needed in order to succeed.

California is the nation's high-tech leader and is home to several of the world's leading nanotechnology research institutions. But leadership does not come automatically, even to California: it must be planned for. If the state takes appropriate steps to leverage its existing advantages and to effectively cope with challenges that may arise, California should be able to maintain its leadership in nanotechnology in the decades to come. Now is the time to lay the foundation for this future.

7.2 Policy Recommendations

California Congressional Delegation

I. **Bring federal money to California via the Boehlert-Honda Nanotechnology Act and the 21st Century Nanotechnology Research and Development Act.** This legislation authorizes $3.68 billion over the next four years for nanotechnology research and development programs at the National Science Foundation (NSF), the Department of Energy (DOE), the Department of Commerce, NASA, and the Environmental Protection Agency. In particular, the California delegation should work together to insure that

Congress fully appropriates the amounts for nanotechnology authorized in the Boehlert-Honda bill, specifically:

- The National Science Foundation should be appropriated \$385 million in FY 2005 and \$424 million in FY 2006;
- The Department of Energy should be appropriated \$317 million for FY 2005 and \$347 million for FY 2006;
- The National Aeronautics and Space Administration should be appropriated \$34.1 million for FY 2005 and \$37.5 million for FY 2006;
- The National Institute of Standards and Technology should be appropriated \$68.2 million for FY 2005 and \$75 million for FY 2006; and the Environmental Protection Agency should be appropriated \$5.5 million for FY 2005 and \$6 million for FY 2006.

The California delegation should pay particular attention to three specific programs that have important benefits to California. They are:

- *Government Industry Cosponsorship of University Research* – GICUR funds the government's share of the Focus Center Research Program (FCRP), a partnership between the semiconductor industry and the Department of Defense to support university research in semiconductors. There are currently five focus centers including the Gigascale Silicon Research Center (GSRC) led by the University of California at Berkeley and the Functional Engineered Nano Architectonics (FENA) Focus Center led by the University of California at Los Angeles. Seven other California universities participate in the program. California's congressional delegation should support an appropriation of \$20 million in FY 2005 to fund the government's share of the \$40 million anticipated in that year.
- *Molecular Foundry* – The Molecular Foundry at Berkeley is a user facility for the design, synthesis and characterization of nanoscale materials. Groundbreaking for the facility is scheduled for January 2004. It is one of five nanoscale science research centers established by the U.S. Department of Energy. California's congressional delegation is urged to fully fund the Energy Department's request for its nanoscale science research centers.
- *NASA Ames* – One of the largest single nanotechnology research centers in the world, NASA Ames is a significant part of NASA's nanotechnology budget and its budgetary requirements in FY 2005 need to be assured.

S189, the 21st Century Nanotechnology Research and Development Act requires the creation of research centers, education and training initiatives, research into societal and ethical implications of nanotechnology, and efforts to transfer technology for commercial uses.

California Legislature

I. **Create a Select Committee on New and Emerging Technologies in each house of the Legislature.** The Senate President pro Tempore and the Speaker of the Assembly should create a Select Committee on New and Emerging Technologies in each house. Alternatively, the current Senate Subcommittee on New Technologies could expand its role to include nanotechnology. The committee could be charged to:

a. Identify significant technology issues that standing and select committees in both houses should be knowledgeable about;

b. Identify emerging technologies that could effect California's industries, employment, or workforce education system;

c. Monitor federal and state government program activities to determine opportunities and difficulties that could impact the development and application of new technologies, including nanotechnology; and

d. Educate the public to ensure that unfounded concerns regarding nanotechnology do not impede thoughtful analysis of its true benefits and risks.

II. **Create nanoethics centers.** Using existing resources, private donations and funding, and federal grants, request its chairs to introduce legislation in an appropriate committee to create one or more nanoethics centers in the state's higher education system for the assessment of nanotechnology's social and ethical implications.

III. **Examine public privacy of nanotechnology sensors and data**. Request the chair of the Senate Subcommittee on New Technologies to examine the impact of nanotechnology sensors and information processing on public privacy. Consideration needs to be given to questions such as:

a. Will fair-use clauses requiring notification on products incorporating sensors be necessary and appropriate?

b. Will the detection of unauthorized sensors in itself require the widespread placement of sensors?

c. If sensors that monitor internal human body conditions can broadcast their information, what controls may be needed to protect a patient's privacy?

Governor's Office

The Governor should:

I. **Establish a Nanotechnology Research and Workforce Advisory Council**. The council should be staffed by the Governor's Office of Planning and Research and should include the Governor's Secretary of Education, representatives for UC, CSU, the state's private universities, CCST (as a member or technical advisor), the California Community Colleges, the Secretary of Labor and Workforce Development Agency, the Secretary of Business, Transportation and Housing Agency, and business representatives such as Northern California Nanotechnology Initiative (NCnano), and others from nanotechnology clusters in the Los Angeles, San Diego, and San Francisco Bay Areas. The Council's charge should be to:

a. Track the development of the state's nanotechnology regional industry clusters;

b. Determine California's relative competitive advantage in critical sectors compared to other states and nations;

c. Use "red teams" drawn from participating state agency staff to identify and recommend ways to address emerging nanotechnology educational and workforce training issues using state and other resources;

d. Create forums, encourage professional associations and others to discuss and evaluate nanotechnology developments in public settings; and

e. On a regular basis, summarize or conduct measures of the public's acceptance of, resistance to, or rejection of nanotechnology in each of its various subfields, clarifying where the primary public concerns and interests lie. Some of these data could be found in surveys of public attitudes, town hall meetings, and other observations of the economic trends and changing labor markets.

The Secretary of Education should:

II. **Create a K-12 Science and Engineering Initiative.** Immediately consider a range of K-12 initiatives that could improve the flow of students, particularly women and other underrepresented groups, into engineering and science careers. CCST and many other organizations have made a number of recommendations to improve science and engineering education and to link it to the community colleges and private institutions of higher learning that could guide this effort.

III. **Insure that nanotechnology is included in the state education science standards.**

The Governor's Office of Planning and Research should:

IV. **Identify outmoded tax incentives** whose value could be transferred to encourage nanotechnology development. Form a state-private industry partnership to consult with the Commission on Tax Policy and the New Economy to identify existing tax incentives that could be terminated on a one-for-one basis and replaced dollar-for-dollar with new ones for nanotechnology.

V. **Encourage local land planning and zoning** such that industrial parks can be sited close to major universities so that proximity advantage can be established.

VI. **Examine siting of nanotechnology manufacturing in California**. Begin to consider possible manufacturing spin-off locations in the state.

College and University Systems

The University of California, California State University system and private universities should:

I. **Create a strategic higher education research and technician workforce training plan for California.** CCST should draw upon its members from all segments of California's higher education system to form a working group to create the strategy and to determine an appropriate means for implementing and tracking it.

II. **Develop a social science nanotechnology curriculum.** The higher education system needs to develop new social science electives as part of undergraduate and graduate curricula to train social scientists to identify and track the risks and benefits of nanotechnology as the technology emerges.

III. **Encourage and attract public and private financing**. Involved institutions should pursue funding as a consortium.

The California Community Colleges Chancellor's Office, and the Dean of the Economic and Workforce Development Program should:

IV. **Inventory Industry Driven Regional Collaborative (IDRC) projects**. The goal would be to look for those linking business to college based workforce training to determine which lessons learned might be applicable to industry driven nanotechnology workforce training.

V. **Establish a nanotechnology workforce training initiative**. A portion of existing IDRC resources could be redirected in the normal funding process to begin development of a nanotechnology workforce training curriculum in each of the three nanotechnology regions. Industry and other higher education systems with significant nanotechnology research, or that have developed a nanotechnology undergraduate curriculum should be invited to participate. This curriculum should include modules that could be added on to existing training programs in biotechnology and related areas.

California State Government Agencies and Departments

I. **Form the Joint Nanotechnology Human, Agricultural, and Environmental Assessment Committee.** The Department of Health Services, Cal/OSHA, California Environmental Protection Agency, Department of Food and Agriculture, and other appropriate agencies and departments, should, at the direction of the Governor, form the Joint Nanotechnology Human, Agricultural, and Environmental Assessment Committee. The committee membership should be drawn from each participating agency and develop a working relationship with CCST to provide technical expertise on an as-needed basis with the state's private and public universities and law schools, commensurate with available funding. The Committee should prepare a yearly briefing for the Governor and the Legislature that:

a. Identifies key human health, environmental, occupational health, food and agricultural areas that nanotechnology could significantly impact;

b. Identifies and analyzes the existing legal and regulatory framework applicable to nanotechnology to determine if the existing framework for workplace health and safety codes may already specify the requirements and procedures needed to determine, for example, if the wide scale production of carbon nanotubes poses health hazards to employees. Regulatory gaps could also be identified;

c. Determines if the current federal or state agency jurisdictions and regulatory responsibilities of existing health, safety, food, and environmental laws for different emerging technologies, particularly those cutting across multiple disciplines, are adequate to protect the health and safety of California's residents and environment. Identifies key questions that should be considered by the Legislature or participating agencies in areas that are not well covered or where regulatory responsibilities are confusing;

d. Identifies workable cost/benefit criteria, including ethical and social impacts that would provide appropriate guidelines for policy making;

e. Identifies a series of "trigger points" in laboratory results that would designate when greater social concern, oversight, and restriction is warranted. These trigger points would give attention to developments that may represent danger as agreed upon by prior considerations;

f. Identifies what should be done to develop a core base of interdisciplinary knowledge, including joint work between nanoscientists and social scientists, and in general explores the possible positive and negative impacts, including ethical issues, which could emerge from current nanotechnology basic science anywhere in the world, but particularly in California and what the health and quality of life impact could be for California's industries and its citizens.

The Labor and Workforce Development Agency should:

II. **Direct the Economic Strategy Panel, with support from the Labor Market Information Division, to identify the components, workforce development and other needs of emerging regional California nanotechnology clusters.**

III. **Direct the Labor Market Information Division, Employment Development Department, to permanently assign an analyst to monitor the emergence of the nanotechnology industry** and related components in the three nanotechnology regions (Los Angeles, San Diego, and the San Francisco Bay Area).

IV. **Continuously update the California Training and Education Providers database** to identify nanotechnology related jobs. Industries to be listed include those involved in: biotechnology, catalysts, chemicals, coatings, devices, electronics, energy, fabrication, instruments, magnetics, materials, metals, mining, nanotubes, optics, packaging, powders, software, spintronics, and textiles.

V. **Instruct the Workforce Investment Board to identify nanotechnology as an emerging manufacturing industry cluster** that should be followed and the necessary training infrastructure appropriate to its stage of development put into place.

VI. **Involve nanotechnology oriented businesses and universities** that are actively transferring nanotechnology to industry when developing workforce training initiatives.

VII. **Train One-Stop staff** to understand and respond to specialized needs of high technology, and nanotechnology using or based on manufacturers in their immediate area. This means training One-Stop staff in the Los Angeles, San Diego, and the San Francisco Bay Area to be responsive to nanotechnology company training needs.

VIII. **Involve university, workforce training, and business** in developing and modifying a workforce training strategy for the industry.

IX. **Instruct the Employment Training Panel to develop goals, objectives and strategies** to enable the panel to increase small nanotechnology businesses' access to the Employment Training Panel program and services.

The Business, Transportation and Housing Agency should:

X. **Form Nanotechnology Regional Interagency Working Groups**. Work with the California Association for Local Economic Development (CalEd) and regional economic development groups (such as the Regional Technology Collaborative in Los Angeles) to form nanotechnology regional interagency working groups in Los Angeles, San Diego, and the San Francisco Bay Area to:

   a. Align state, local, federal, industry, non-profits, and other sources with regional emerging industry needs in geographic areas.

   b. Assist with providing venture capitalists and angels with obtaining appropriate information for vetting nanotechnology start-up companies for funding.

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3. Nanostructure Science and Technology: A Worldwide Study.

This report reviews the status of research and development in nanoparticles, nanostructured materials, and nanodevices worldwide, with particular focus on comparisons between the United States and other leading industrialized countries. Topics covered include particle synthesis and assembly, dispersions and coatings of nanoparticles, high surface area materials, functional nanoscale devices, bulk behavior of nanostructured materials, and biological methods and applications. The final chapter is a review of related government funding programs around the world. Siegel, R.W., E. Hu, and M.C. Roco, eds., Nanostructure Science and Technology: A Worldwide Study., NSTC/CT/IWGN, 1999.

4. Nanotech: the Tiny Revolution.

This white paper is a preview of The Nanotechnology Opportunity Report™ which provides a thorough analysis of the global nanotechnology market and of the key technologies coming to market now and in the near future. It also includes an extensive guide to the 455 public and private companies, 95 investors, and 271 academic institutions, and government entities that are involved in the near-term applications of the technology worldwide. Analysis is provided on both markets & technologies, at a price of $1995. Hollister, P., Nanotechnology- the Tiny Revolution., July 2002, CMP cientifica: www.cientifica.com.

5. Economic Perspectives of Nanotechnology: Enormous Markets for Tiny Particles.

Growth forecast of the world market of nanomaterials from the stand point of BASF Corporation. Being one of the world leaders in chemical manufacturing, BASF's point of view may be valuable in assessing the market for nanomaterials. Ebenau, A., Economic Perspectives of Nanotechnology: Enormous Markets for Tiny Particles, BASF Future Business GmbH, Ludwigshafen: Mannheim, October 2002.

6. CORDIS.

This web site provides information on the EU's efforts and achievements in nanotechnology and science and technology in general. http://www.cordis.lu/nanotechnology/.

7. Sci-Tech Focus Report.

Concise discussion of the growth of nanotechnology in Korea. "Survey of Korea's Nanotechnology", Sci-Tech Focus; 2002, http://nr.stic.gov.tw/ejournal/SciTechFocus/SciTechFocus_e.htm. p. 5.

8. Asia Pacific Nanotech Weekly.

Publishes weekly reports, commentary and analyses on nanotechnology activities in Asia Pacific. The reports are in PDF format and freely accessible. Liu, L., Asia Pacific Nanotech Weekly, http://www.nanoworld.jp/apnw/.

9. Nanoscale Chemicals and Materials—An Overview on Technology, Products and Applications.

Compiled by SRI Consulting, a subsidiary of SRI International, this by far is the most informative report on Asia; it provides data on current and future budget plans of Asian and European countries, along with the core emphasis technologies. Fink, U., et al., Nanoscale Chemicals and Materials-An Overview on Technology, Products and Applications. December 2002, http://scup.sric.sri.com/Enframe/Report.html?report=NANOT000&show=Navigation.html.

10. Nanotechnology Market and Company Report 2003.

The definition of the term "nanotechnology" was discussed with an international advisory board. The nanotechnology world market is predicted for specific product categories in each of the four nanotechnology segments. The company profiles are identified via various databases, conferences and internet researches. These profiles include information such as founding year, revenue, number of staff and short descriptions of key business activities with respect to nanotechnology. For an analysis of the present status and future visions of nanotechnology, interviews with 48 leading experts were carried out. The experts' responses on the future visions and future products serve as an indicator of future developments from the present point of view. Stark, D., Finding Hidden Pearls: Nanotechnology Market and Company Report 2003. 2003, http://www.nanoreport.de/home.html.

11. Current Medical Technologies, Applications & Market Opportunities in Nanotechnology & MEMS, 2002-2012.

While much of the enormous potential in nanotechnology and micro-electro-mechanical systems (MEMS) is at least a few years from beginning to materialize, the existence of substantial current revenue, current profits and a wide array of current activity demands scrutiny now by any entities seeking to truly capitalize on this market. This report on nanotechnology and MEMS is a detailed market and technology assessment and forecast of the products and technologies involved in the medical application of MEMS and nanotechnology. The report details the current and emerging products, technologies and markets in the medical use of MEMS and nanotechnology. Specifically, the report comprehensively details the clinical applications, the status of products and technologies under development, the current/forecast market for each major application, the current or likely competitors and their positions in the market, and the opportunities for current or hopeful competitors in this field. Driscoll, P., Current Medical Technologies, Applications & Market Opportunities in Nanotechnology & MEMS, 2002-2012. 2003: http://www.mediligence.com/rpt-t601.htm.

USA

12. Implications of Emerging Micro- and Nanotechnologies.

An evaluation of the current trends in micro and nanotechnology for the Air Force. Increased information capabilities, miniaturization, new materials and increased functionality and autonomy emerged as the four main themes for emerging technologies. Brueck, S.R.J., Implications of Emerging Micro-and Nanotechnologies. 2002: Washington D.C.

13. Societal Implications of Nanoscience and Nanotechnology.

This report was created right before the commencement of the NNI in 2001. Current status is documented in section I.2.2.5. of this report. Roco, M.C. and W.S. Bainbridge, eds. Societal Implications of Nanoscience and Nanotechnology. NSET Workshop Report, NSET: Arlington, Virginia, March 2001.

14. The National Nanotechnology Initiative: The Initiative and Its Implementation Plan.

The purpose of the initiative was to support long-term nanoscale research and development leading to potential breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and healthcare, environment, energy, chemicals, biotechnology, agriculture, information technology, and national security. The effect of nanotechnology on the health, wealth, and lives of people could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in this century. Downey, M.L., ed. National Nanotechnology Initiative: The Initiative and Its Implementation Plan. NSTS/CT/NSET: Washington D.C. 144. 2000.

15. The National Nanotechnology Initiative FY 2004 Budget Request.

NNI FY 2004 Budget, at http://www.nano.gov/fy2004_budget_ostp03_0204.pdf.

16. National Nanotechnology Initiative: From Vision to Commercialization.

This meeting was designed to update attendees on the most promising nanotech advances. The meeting would feature status reports by the participating U.S. Government Departments and Agencies and the Nanoscale Science and Engineering Centers addressing:

- The main focus areas of nanotech research for FY 2002 and FY 2003
- The primary research objectives and associated timelines
- Highlights of research to-date and examples of the most promising developments
- Important challenges that need to be overcome
- The potential for near-term commercial applications and their estimated time-frames
- Other commercial applications that could be derived from the research and their estimated time-frames
- Efforts to transition such developments into the private sector
- Solicitations, proposals, and grants
- National Nanotechnology Initiative. From Vision to Commercialization, April 2003, http://www.infocastinc.com/NNI/home.asp.

17. Nanotechnology's Power Brokers.

The team at Forbes/Wolfe Nanotech Report surveyed leading investors, scientists, corporate executives and high-ranking government officials providing a jump on who the top movers and shakers are in nanotech. Survey responses were combined with quantitative criteria to arrive at the final rankings. Wolfe, J., "Nanotechnology's Power Brokers," Nanotech Report. March 2003, p. 1-8, www.forbesnanotech.com.

18. U.S. Nanotechnology 2002: Technologies, Application Development, M&A, Patent Disputes, Markets and Business Opportunity.

Gives an insightful overview of nanotechnology. The report analyzes how this technology works and how it will apply to the consumer market in the near future. The report also details the activities of private and government innovators involved in the highly budgeted nanotechnology R&D arena. This technology, which uses the most miniscule of building-blocks as a base for technological innovations will soon revolutionize the commercial world. MRG, U.S. Nanotechnology 2002: Technologies, Application Development, M&A, Patent Disputes, Markets and Business Opportunity, 2002, http://www.mrgco.com/TOC_FK_Nanotechnology_2002.html.

19. 21st Century Nanotechnology Research and Development Act

This legislation, signed on 12/3/2003, puts into law programs and activities supported by the NNI. The authorization bill calls for $3.68 Billion for nanotechnology R&D for FY 2005 - 2008. http://www.nano.gov/html/news/PresSignsNanoBill.htm.

California

20. Preparing for the Next Silicon Valley: Opportunities and Choices.

The Next Silicon Valley initiative is working to shape both a framework for understanding and communicating what is happening in the Valley economy, and a process for engaging leaders in a regional discussion of the opportunities and choices for the next wave of innovation. This paper identifies the economic opportunities and risks associated with the evolving convergence of biotechnology, nanotechnology and information technology. The purpose of this paper is to stimulate discussion and action in preparing for the next wave of social and technological innovation. Henton, D., et al., Preparing for the Next Silicon Valley: Opportunities and Choices, Joint Venture: June 2002, www.jointventure.org.

21. State Technology and Science Index: Comparing and Contrasting California.

Expanding clusters of existing technologies and emerging science-based technologies formed will be critical factors in determining economic winners and losers in the first half of the 21st century. As economic activity is based more on intangible assets, those states with vibrant technology clusters will experience superior economic growth. It is imperative for state and local development officials and business leaders to promote high-tech expansion and cluster formation. Although high tech is not the only development strategy to pursue, it will be the key distinguishing feature of regional vitality in the 21st century. States that recognize these changes and alter course quickly will be ahead in the economic development game. DeVol, R.C., R. Koepp, and F. Fogelbach, State Technology and Science Index: Comparing and Contrasting California. Milken Institute: September 2002, http://www.milkeninstitute.org/publications/publications.taf?function=detail&ID=163&cat=ResRep.

22. Nanotechnology Yellow Pages.

Generated by Larta, this is a somewhat out of date description of some of the research being carried out in academic and commercial setups in the Southern California region. This report portrays the most prominent themes of California's endeavors in the field of nanotechnology. It does not highlight the diverse scientific developments, restricted primarily to academic research laboratories, that gives the southern California region its paramount position in the global nanotechnology map at these early stages. Foster, L., Nanotechnology Yellow Pages. Larta: 2001, www.larta.org.

II. CONFERENCE PROCEEDINGS AND INDIVIDUAL PRESENTATIONS

Worldwide Studies

23. Promoting Japanese-Style Nanotechnology Enterprise.

An analysis of Japan's strategy in developing nanotechnology. The presentation emphasizes that strategic alliances across national boarders may help Japan acquire the leading role in the global market. It gives a useful comparison of key technologies owned by the U.S. and Japan. KAMEI, S.-i., Promoting Japanese-style Nanotechnology Enterprises (The Need for Strategic International Alliances). 2002: http://www.intv.net/ftmw/DrKamei022602.pdf.

USA

24. Proceedings of EPA Nanotechnology and the Environment: Applications and Implications (STAR Progress Review Workshop).

Collection of papers presented in the EPA conference addressing the impact of the growth and development of nanomaterials and nanotechnology from EPA's standpoint. Karn, B. and N. Savage, EPA Nanotechnology and the Environment: Applications and Implications STAR Progress Review Workshop, The Office of Research and Development's National Center for Environmental Research, 2002.

25. Nanotechnology Innovation for Chemical, Biological, Radiological, and Explosive (CBRE): Detection and Protection.

A workshop on May 2-3, 2002, was organized by the American Vacuum Society, Inc. (AVS) and coordinated with a meeting of the AVS Science and Technology Society held in Monterey, California on May 1 and 2, 2002. The workshop was supported in part by the NNCO. This report summarizes the workshop's conclusions concerning the opportunities and challenges for nanoscience and technology research as applied to the NNI Grand Challenge on Chemical, Biological, Radiological, and Explosive (CBRE) Detection and Protection. Baker, J., et al., Nanotechnology Innovation for Chemical, Biological, Radiological, and Explosive (CBRE): Detection and Protection, November 2002, p. 32.

26. Nanoscale Science, Engineering and Technology in DOE's Office of Basic Energy Sciences. Research Directions and Nanoscale Science Research Centers.

This brochure briefly discusses the challenges of science at the nanoscale and DOE's role in addressing them. It includes a brief description of the Basic Energy Sciences (BES) research program, and the new Nanoscale Science Research Centers are introduced. These user facilities will provide the nation's research community with world-class resources for the synthesis, processing, fabrication, and analysis of materials at the nanoscale. BES, D., Nanoscale Science, Engineering and Technology in DOE's Office of Basic Energy Sciences: Research directions and nanoscale science research centers, 2003, p. 20.

27. NanoBusiness 2003.

The NanoBusiness Conference brings together leaders from business, government, academia and the financial community, providing attendees with all the tools and information required to push nanotechnology research and application development toward commercialization. 2003, N., The official conference of the Nanobusiness Alliance: http://www.nanobusiness2003.com/index.shtml.

28. Molecular Manufacturing: Societal Implications of Advanced Nanotechnology.

In this U.S. House of Representatives Committee on Science hearing, more research into the societal impacts and ethical responsibilities of molecular manufacturing was urged. Witnesses praised H.R. 766, the Nanotechnology Research and Development Act of 2003, sponsored by Committee Chairman Sherwood Boehlert (R-NY) and Rep. Mike Honda (D-CA), as an important step toward achieving that goal. The full Committee hearing is available at [http://www.house.gov/science/hearings/full03/index.htm] Peterson, April 9, 2003, 2003; Tringe, 2003 #24;, April 9, 2003, 2003.

California

29. Nano Republic .

As in 2002, the conference was held on July 10, 2003 in Pasadena, California, and was chaired by Dr. Jim Heath of Caltech. The conference is produced by Larta, a prominent think tank for technology businesses, in collaboration with Caltech, the California NanoSystems Institute, Rockwell Scientific Company, UCSB, UCLA, USC, and UCI. The Nano Republic Conference discussed recent developments in creating actual products and services based on nanotechnologies. The program featured presentations and discussion by world leaders from industry and academia on topics such as materials, design and instrumentation, components (simple devices), and systems (complex devices). Larta, Nano Republic. 2003: http://www.larta.org/nanorepublic/index.htm.

III. CENTERS AND ORGANIZATIONS IN CALIFORNIA

30. California NanoSystems Institute(CNSI) .

The vision of the CNSI is to establish a coherent and distinctive organization that serves California and national purposes and that is embedded on the UCLA and UCSB campuses. The CNSI will be a world-class intellectual and physical environment that supports collaboration among California's university, industry and national laboratory scientists. UCLA and UCSB, California NanoSystems Institute, http://www.cnsi.ucla.edu/mainpage.html.

31. Center for Nanoscale Science and Engineering (CNSE).

UCR in its current phase of strong growth is building a pre-eminent program in Nanotechnology through the establishment of the CNSE. Nanomedicine, where nanomaterials and nanodevices are brought to bear on biological processes and medical ailments is CNSE's thrust area. The effort that UCR is mounting in nanotechnology and its outreach in the Inland Empire will start to catalyze the location of high-tech industry in the Inland Empire.

32. Center for Nanoscience Innovation for Defense (CNID).

In addition to the campus center, UCR joined UCLA and UCSB in July 2002 to form the Center for Nanoscience Innovation for Defense (CNID), an alliance created to facilitate a rapid transition of research innovation in the nanosciences into applications for the defense sector. The three UC institutions will equally share U.S. government allocations of about $20 million. The Defense Advanced Research Project Agency (DARPA) and Defense MicroElectronics Activity (DMEA) sponsor the three-campus CNID. The center aims at the control and understanding of nanoscale materials, with applications in information and communications technology.

33. Northern California Nanotechnology Initiative .

The Northern California Nanotechnology Institute (NCnano) Initiative is a regional economic development program committed to building the world's leading nanotechnology cluster in Northern California. Their major organizational goals are to bring $6 billion in nanotechnology investment and grant money into the Northern California region and to create 150,000 new local jobs. Through creation of the NCnano, they will provide the unifying fabric integrating Universities, Research Labs, Businesses, Capital, Local and Regional Governments and Entrepreneurs. The challenge is fostering the creation of a dynamic environment where new ventures, spinouts and established companies can mutually prosper in the new, nanotechnology-driven, global technology economy. Initiative, T.N.C.N., NC nano. 2003; http://www.ncnano.org/index.php.

Jr, R.P., House Approves Boehlert-Honda $2.36 Billion Nanotechnology Legislation Bill to Boost Silicon Valley Economy. 2003, May 7: http://www.ncnano.org/index.php?module=ContentExpress&func=display&ceid=28.

34. Bay Area Nanotechnology Initiative (BANI).

BANI was initiated in April by the San Francisco Center for Economic Development in conjunction with leaders from industry and academia in the Bay Area and Silicon Valley. BANI is currently undertaking a regional assets assessment to assist the region to retain its pre-eminent position as the leader in research and development of nanoscience and nanotechnology. BANI has been building partnerships with industry, academia, research laboratories, venture capitalists and existing nanotechnology start ups in the San Francisco Bay Area and Silicon Valley. Piasente, C., R. Achtenberg, and T. Ewing, Bay Area Nanotech Initiative Receives State Funding For Regional Collaboration to Capitalize on Emerging Industry, 2003, May 12, http://www.sfchamber.com/nanotech_initiative.htm.

35. Bay Area Economic Forum.

The Bay Area Economic Forum conducts projects and initiatives which mobilize leaders from the public and private sectors, higher education, labor and the community to work together to strengthen the region's economic climate and address its major challenges. With its sponsors, the Bay Area Council and the Association of Bay Area Governments, and partner organizations representing constituencies throughout the region, the Forum addresses issues of overarching concern to the Bay Area and its economic future. The Bay Area Science Innovation Consortium (BASIC) is in the process of producing a Bay Area regional nanotechnology futures report, highlighting and demonstrating the importance and competitiveness of the region's R&D infrastructure in the field. Forum, B.A.E., BASIC, http://www.bayeconfor.org/baefdesc3.htm.

APPENDIX A: PRINCIPAL AUTHORS

Wasiq Bokhari

Wasiq Bokhari received his Ph.D. in physics from the Massachusetts Institute of Technology. He was part of the team that discovered the top quark at the Fermi National Accelerator Laboratory. He has done post-doctoral research on fundamental physics and has more than 50 scientific publications and presentations to his name. He was also part of a small team that designed next generation particle detectors at Fermilab. As an entrepreneur, he has been part of the founding teams of various ventures including Clickmarks, an enterprise software provider. As the senior vice president of Products, he oversaw the creation and successful launch of the company's award-winning software. Bokhari has spoken on various industry forums as an invited speaker. He is cited as a co-inventor on ten industry patents.

Michael R. Darby

Michael R. Darby is the Warren C. Cordner Professor of Money and Financial Markets in the John E. Anderson Graduate School of Management and in the Departments of Economics and Policy Studies at the University of California, Los Angeles, and is director of the John M. Olin Center for Policy in the Anderson School. Concurrently, he holds appointments as chairman of The Dumbarton Group, research associate with the National Bureau of Economic Research, consulting economist with City National Bank, and adjunct scholar with the American Enterprise Institute. He also serves as associate director for the Center for International Science, Technology, and Cultural Policy in the School of Public Policy & Social Research at UCLA. Darby received his A.B. summa cum laude from Dartmouth College, and his M.A. in 1968 and Ph.D. in 1970 from the University of Chicago.

Edward V. Etzkorn

Edward V. Etzkorn is currently a Ph.D. candidate in the Materials Department at the University of California at Santa Barbara, where his research has focused on semiconductor crystal growth, stress development, and fracture. He has also recently completed a Christine Mirzayan Science and Technology Policy Internship at the National Academies, working with the NRC Board on Physics and Astronomy. Etzkorn received his B.S. in applied physics in 1995 from the California Institute of Technology.

Susan Hackwood

Susan Hackwood is currently professor of electrical engineering at the University of California, Riverside and executive director of the California Council on Science and Technology. Hackwood received a Ph.D. in solid state ionics in 1979 from DeMontfort University, UK. Before joining academia, she was department head of Device Robotics Technology Research at AT&T Bell Labs. In 1984 she joined the University of California, Santa Barbara as professor of electrical and computer engineering and was founder and director of the National Science Foundation Engineering Research Center for Robotic Systems in Microelectronics. In 1990, Hackwood became the founding dean of the Bourns College of Engineering at the University of California, Riverside.

Robert C. Haddon

Robert C. Haddon is a distinguished professor of chemistry at the University of California, Riverside. He received a B.Sc. in chemistry (1966), Melbourne University, Australia and a Ph.D. in chemistry (1971), Pennsylvania State University. He formerly worked with Bell Laboratories, AT&T Lucent Technologies. Haddon's research interests have been directed toward the electronic structure and properties of molecules and materials, with particular emphasis on transport, magnetism, superconductivity, device fabrication and miniaturization, and the discovery of new classes of electronic materials.

Gus A. Koehler

Gus A. Koehler is a political sociologist, and principal and co-founder of Time Structures. He is an adjunct faculty member of the Department of Business and Public Administration at the University of Southern California. Koehler received his Ph.D. in political science and sociology from the University of California, Davis. His dissertation examined the relationship between concepts of time and space and current ideas about democratic theory. Koehler served as a senior policy analyst with the California Research Bureau where he conducted policy research for the California State Legislature, the Governor and other elected officials. His current research responsibilities include identifying and evaluating state economic development issues and remedial strategies.

Sandip Niyogi

Sandip Niyogi is currently a graduate student in the Chemistry Department at the University of California, Riverside.

Anthony A. Waitz

Anthony A. Waitz has 18 years of experience in technology development, management and strategy. Most recently he was with Synopsys Inc. where he was responsible for the strategy of silicon IP. Prior to this, he was a director of engineering at Synopsys, where he ran six engineering groups focused on the design and delivery of silicon IP products. Waitz came to Synopsys through the acquisition of Silicon Architects in 1995, of which he was a co-founder. Outside of silicon IP, Waitz has had a diverse technical background spanning areas such as research in parallel processors and the development of an early optical networking system. Waitz holds masters degrees from Stanford School of Engineering and the Stanford Graduate School of Business.

Lynne G. Zucker

Lynne Zucker is professor of sociology (1989-present) and policy studies (1996-present) and serves as director (1996-present) of the Center for International Science, Technology and Cultural Policy in the School of Public Policy & Social Research at UCLA. Concurrently, she holds appointments as research associate with the National Bureau of Economic Research, and was previously a consulting sociologist with the American Institute of Physics. Zucker received her A.B. with distinction in sociology & psychology from Wells College in 1966. She received her M.A. in 1969 and Ph.D. in 1974 from the Sociology Department of Stanford University.

APPENDIX B: REVIEWERS

CCST Nanotechnology Committee

Arthur N. Chester

Retired President, HRL Laboratories, LLC

Arthur N. Chester is retired president and general manager of HRL Laboratories, a limited liability company owned jointly by The Boeing Company, General Motors and Raytheon Company, and serves as a central R&D laboratory for all three corporations. Chester is recognized as a pioneer in laser technology and an authority in the field of technology management. Chester headed HRL beginning in 1988. From 1988 through 1997, he also served as senior vice president, Research and Technology for Hughes Electronics. A graduate of the California Institute of Technology and the University of Texas, Chester serves on the UC MICRO Board and on Advisory Boards at UCLA, USC and UCR. He has published numerous technical papers and edited 15 books, and is a consultant to the U.S. Department of Defense.

Paul C. Jennings (CCST Fellow)

Professor Emeritus, Civil Engineering/Applied Mechanics, California Institute of Technology

Paul C. Jennings is professor emeritus in the Department of Civil Engineering and Applied Mechanics at Caltech . He served as executive officer for Civil Engineering and Applied Mechanics, and as chairman of the Division of Engineering and Applied Science from 1985 to 1989. He was Caltech's vice president and provost between 1989-95, and later served as acting vice president for Business and Finance. He was a member of the Board of Directors of Enresco, Inc., in Colorado Springs and served two years on the teaching staff at the U.S. Air Force Academy, Department of Mechanics. Jennings is a member of the National Academy of Engineering, past president of the Seismological Society of America, and past president of the Earthquake Engineering Research Institute.

William C. Y. Lee (CCST Fellow)

Chairman, LinkAir Communications

William C. Y. Lee is chairman of LinkAir Communications. He was vice president and chief scientist of Global Technology for Vodafone AirTouch, manager of the Advanced Development Department at ITT Defense Communications Division, and from 1964 to 1979, he was with Bell Laboratories, where he was a pioneer in mobile radio communications studies. Lee was recognized with the Bell Labs Dedicated Service Award, the ITTDCD Technical Contribution Award and the IEEE VTS Avant Garde Award. In 1998, he was awarded the CDMA Industry Achievement Award for his technical achievements. Lee is a distinguished Alumnus of Ohio State University, where he obtained his Ph.D. in electrical engineering.

C. Kumar N. Patel (CCST Fellow)
Professor, Department of Physics, University of California, Los Angeles

C. Kumar N. Patel is professor of physics and astronomy, chemistry, and electrical engineering at the University of California, Los Angeles. From 1993 to 1999, he was the vice chancellor of Research at UCLA. Prior to this he was executive director of the Research, Materials Science, Engineering and Academic Affairs Division at AT&T Bell Laboratories. He is the past president of the American Physical Society (1995) and the Sigma Xi, The Scientific Research Society (1993-1995). Patel received his B.E. in telecommunications from the College of Engineering in Poona, India in 1958. He received M.S. and Ph.D. degrees in electrical engineering from Stanford University in 1959 and 1961, respectively. In 1988, he was awarded an honorary Doctor of Science degree from the New Jersey Institute of Technology.

Robert Spinrad
Consultant

Bob Spinrad retired from Xerox in 1998, where he last served as vice president, technology strategy, and earlier, as director of Xerox PARC. Bob is currently a member of the University of California President's Engineering Advisory Council. He also serves on the RAND Graduate School's Board of Governors; on the National Research Council's Division on Engineering and Physical Sciences, on its Study Group on "Global Networks and Local Values;" on the American Association for the Advancement of Sciences Committee on Science, Engineering and Public Policy; on the Berkeley Center for Law and Technology's Board of Advisors; on the Jet Propulsion Laboratory's (Caltech) Commercial Advisory Council and on the National Reconnaissance Office Advisory Council. Spinrad holds a doctorate from MIT and is a member of the National Academy of Engineering.

Nanotechnology Experts

Evelyn L. Hu
Professor, Departments of Materials and ECE, University of California, Santa Barbara

Scientific Co-Director, California NanoSystemsInstitute

Before joining the University of California, Santa Barbara in 1984, Hu worked at AT&T Bell laboratories, developing microfabrication and nanofabrication techniques that enabled the formation of superconducting and semiconducting devices and circuits. She is the Scientific Co-Director of the newly-formed California Nanosystems Institute, a UCLA-UCSB collaborative California Institute for Science and Innovation. She has previously served as the director of QUEST, an NSF Science and Technology Center for Quantized Electronic Structures, and the director of the UCSB node of the National Nanofabrication Users Network. She serves on the Board of Reviewing Editors for Science, and on the editorial boards for the Virtual Journal of Nanoscale Science& Technology and Nanoletters. She is a member of the National Academy of Engineering, a recipient of the AAAS Lifetime Mentor Award, a fellow of the IEEE, APS, and the AAAS, and holds an honorary Doctorate of Engineering from the University of Glasgow. Hu received her B.A. in physics from Barnard College in 1969, and her M.A. and Ph.D. in physics from Columbia University in 1971 and 1975, respectively.

Meyya Meyyappan
Director, Center for Nanotechnology, NASA AMES Research Center

Meyya Meyyappan is project manager as well as senior scientist for nanotechnology at NASA Ames Research Center in Moffett Field. He is a member of the Interagency Working Group on Nanotechnology, established by the Office of Science and Technology Policy. His research interests include plasma processing, carbon nanotube synthesis and application development. His group consists of about 35 scientists engaged in nanotechnology, computational electronics and optoelectonics, and plasma processing. Meyyappan's nanotechnology group has been engaged in carbon nanotube based nanotechnology research. This group has done pioneering work on evaluation of the properties of carbon nanotubes.

Industry and Government Representatives

Daryl G. Hatano
Vice President, Public Policy, Semiconductor Industry Association

Daryl Hatano is the vice president of Public Policy for the Semiconductor Industry Association, with responsibilities for the association's international trade, legislative and workforce strategy programs. Hatano has an undergraduate degree in political science and economics from the University of California, Davis, a juris doctorate from the UC Davis Law School and a masters in business administration from the UC Berkeley Haas School of Business Administration. He is also a member of the California Bar. Hatano has published articles in the area of business and public policy in the *California Management Review*, the *American Journal of Business Law*, and *Managerial Planning.*

Jeffrey Newman
Partnership Manager, Commerce and Technology Partnership; Business, Transportation and Housing Agency

Jeffrey Newman is partnership manager of the Commerce and Technology Partnership at the Business, Transportation and Housing Agency. He was formerly the partnership manager in the Division of Science, Technology and Innovation (DSTI), California Technology, Trade and Commerce Agency. His responsibilities have included overall management and guidance of DSTI technology-based economic development programs: the Manufacturing Technology Program, the California Technology Investment Partnership matching grant program, the Next Generation Internet program, the Rural E-Commerce program and the Regional Technology Alliances (a network of regionally responsive, industry driven private/public partnerships). Newman has seven years of experience in the private sector as an electronics engineer. Newman holds a bachelor's and masters in physics from California State University. He has completed course work toward a Ph.D. in human and organizational systems at the Fielding Institute.

APPENDIX C: CALIFORNIA COUNCIL ON SCIENCE AND TECHNOLOGY

2004 BOARD MEMBERS

Karl S. Pister, *Board Chair*, CCST
Former Vice President-Educational Outreach, University of California
Chancellor Emeritus, University of California, Santa Cruz

Lloyd Armstrong, Jr., *Provost and Senior Vice President, Academic Affairs*
University of Southern California

Warren J. Baker, *President*
California Polytechnic State University, San Luis Obispo

Arthur Bienenstock, *Vice Provost and Dean of Research and Graduate Policy and Professor of Materials Science and Engineering and of Applied Physics*
Stanford University

Bruce B. Darling, *Senior Vice President, University Affairs*
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John S. Foster, Jr., *Consultant*
Northrop Grumman Space Technology

David L. Goodstein, *Vice Provost and Frank J. Gilloon Distinguished Teaching and Service Professor*
California Institute of Technology

Susan Hackwood, *Executive Director*
California Council on Science and Technology

Charles E. Harper, *President and CEO*
Sierra Monolithics, Inc.

C. Judson King, *Provost and Senior Vice President, Academic Affairs*
University of California

Victoria Morrow, *Executive Vice Chancellor*
California Community Colleges

Robert J. Spinrad, *Consultant*

Henry T. Yang, *Chancellor and Professor of Mechanical Engineering*
University of California, Santa Barbara

2004 COUNCIL MEMBERS

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Provost and Senior Vice President, Academic Affairs, University of California

Michael R. Anastasio, *Director*, Lawrence Livermore National Laboratory

David Auston, *President*, Kavli Foundation

Francine Berman, *Director*, San Diego Super Computer Center, University of California, San Diego

Alfonso Cárdenas, *Computer Science Professor*, University of California, Los Angeles

Arthur N. Chester, *Retired President and General Manager*, HRL Laboratories, LLC

Michael T. Clegg, *Distinguished Professor of Genetics and Director*, College of Natural and Agricultural Sciences, Institute of Genomics, University of California, Riverside

Linda R. Cohen, *Professor of Economics*, University of California, Irvine

Lawrence B. Coleman, *Vice Provost for Research*, University of California

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